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CHAPTER ONE

Time for Meaning: Electrophysiology Provides Insights into the Dynamics of Representation and Processing in Semantic Memory

Kara D. Federmeier *and* Sarah Laszlo

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Abstract

At least since the time of Aristotle, humans have been fascinated with trying to understand how meaning is represented in what, in modern terms, has come to be known as semantic memory. Behavioral science, computational modeling, neuropsychology, hemodynamic imaging, and electrophysiological techniques have all been applied to the task of delineating how semantic memory is instantiated in the brain. As reviewed in this chapter, the collective data from

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these methods are providing an increasingly detailed picture of the functional and neural organization of semantic memory. What remains less clear are the dynamics of how meaning is accessed and used. Those dynamics, however, are beginning to be revealed by data from temporally sensitive measures, such as electrophysiology. In particular, studies of the N400 event-related potential (ERP) component suggest that considerations of time may hold the key to understanding how information represented in disparate areas of the brain comes to be bound in the structured-yet-flexible manner that is the hallmark of human semantic processing.

1. Introduction

Imagine walking into a library and finding books, periodicals, and maps shelved and stacked in a haphazard, nearly random fashion—a cluster of books of the same color, a shelf of large books, a pile of recently used periodicals. The usefulness of such a library would be quite limited because, although it might contain a great deal of information, that information would be nearly impossible to find in any reasonable amount of time. In fact, this was the state of most libraries in the United States prior to 1876 when Melvil Dewey first published his now widely used system of library organization, the Dewey Decimal system. This classification system and the others that followed it are arguably the cornerstone of libraries and other information reservoirs because such systems transform information warehouses into information databases.

Like libraries, human brains are storehouses of vast amounts of different kinds of information. In what is typically referred to as semantic memory, the human brain stores information about objects, including what they look, sound, feel, smell, and taste like, how they move, and how they are used, and about places, actions, and events. Information about the faces, voices, and biographies of people in the movies and in the neighborhood is also maintained, as is information about words, including their spelling, sound, and meaning, and the patterns in which they cooccur. And, like libraries, human brains must not only store all of this information but also make it available for use, in varied contexts and often in only a few hundred milliseconds or less. The question of how information is represented in and accessed from semantic memory is therefore a central one for both psychology and neuroscience. It has implications for how knowledge is acquired and lost (with age, disease, or trauma), what kinds of information will become available in response to a particular stimulus, and when and how knowledge will be used in a particular task situation (i.e., what inferences and what errors are likely to be made). Indeed, the study of semantic memory is arguably the study of the filter through which the human being views and interacts with her world.

The organization and dynamics of semantic memory have been studied with a wide variety of perspectives and techniques. As will be reviewed in the first part of this chapter, neuropsychological and hemodynamic imaging studies have converged to provide a picture of how meaning-related information is organized in the brain and where it is stored. In particular, it is becoming increasingly clear that meaning is represented in a highly distributed fashion and that multiple brain areas are involved in semantic access and processing. This emerging understanding of semantic representation in the brain, however, emphasizes the critical "binding problem," which asks how distributed feature information is brought together to create the integrated concepts that humans experience, remember, and use to communicate and reason. The second part of the chapter, therefore, discusses how considerations of time, and data provided by temporally precise measures such as event-related brain potentials, can speak to the dynamics of semantic access and thereby enrich the understanding of how the brain represents and processes meaning.

2. Conceptual Structure and Neural Structure

> Words signify substance, quality, relation, place, position, state, action or affection . . . roughly, examples of substance are 'man' or 'horse', of quantity such terms as 'two cubits long' or 'three cubits long', of quality such attributes as 'white', 'grammatical' . . ..
>
> Aristotle (350 B.C.E.), *The Categories*

Concepts are mental representations of a type or class, often including a great deal of multifaceted information. For example, the concept of dog is likely to include information about its typical shape and size, the feel of its fur, and the sound of its bark, as well as more abstract information such as what it is likely to eat, how it behaves, its usual lifespan, and so forth. The idea that concepts may be grouped into categories, which are organized by similarity and structured into taxonomies, has a longstanding tradition in western philosophy (e.g., Aristotle, 2006; Kant, 1996), and continues to be a prominent view in cognitive psychology (see review and critiques in Murphy, 2002). Approaches to understanding semantic memory that utilize techniques from neuropsychology and cognitive neuroscience have generally assumed that this conceptual information resides in a specialized semantic system, which is accessed via connections between unimodal, perceptual areas (e.g., the left fusiform gyrus in the case of visual orthographic input or the primary and secondary auditory cortices in the case of acoustic input) and "association areas" (especially the left inferior prefrontal cortex and perisylvian cortex) that process information originating from multiple sensory modalities.

Within this framework, two distinct kinds of questions have been asked. The first arises out of traditional cognitive theories of semantic memory, which posit that conceptual information resides in a semantic store, where it is represented in an "amodal" format (i.e., a format that does not make reference to the physical form by which that information was originally delivered; Pylyshyn, 1980). Studies in this line of work have therefore sought to delineate the brain areas that are involved in processing for meaning that occurs regardless of input modality (e.g., auditory words, visual words, pictures) or type (e.g., action verb, concrete noun). Research examining this question often adopts the approach, which reaches back to PET studies in the late 1980s and early 1990s (e.g., Petersen & Fiez, 1993; Petersen, Fox, Posner, Mintun & Raichle, 1989), of using multiple subtractions to try to isolate areas selectively involved in semantic processing. A core assumption of this approach is that areas that participate in amodal semantic processing should be more active during semantic tasks than during, for example, phonological, orthographic, or complex perceptual tasks performed on the same items. They should also be more active when processing words than when processing various types of equally perceptually complex, but meaningless, controls such as pseudowords, illegal strings of letters or combinations of sounds, or visual or auditory noise.

The second question typically addressed by cognitive neuroimaging and neuropsychological studies of semantic organization is essentially the inverse of the first: what brain areas are involved in semantic processing but are not independent of input modality or category? For example, are there separable areas involved in processing auditory and visual words for meaning (e.g., Marinkovic et al., 2003)? Do different cortical areas subserve the representation of living and nonliving entities (e.g., Leube, Erb, Grodd, Bartels, & Kircher, 2001; Thompson-Schill, Aguirre, D'Esposito, & Farah, 1999) or other types of categories? This second question builds on initial findings in neuropsychology suggesting that focal brain lesions can result in the impairment of semantic knowledge about particular semantic categories (e.g., living vs. nonliving things, abstract vs. concrete words; Warrington & Shallice, 1984). As will be discussed in more detail, growing evidence that semantic information may be distributed across a large number of brain areas, many of which are clearly modality specific, raises the important question of how integrated conceptual entities come to be built from distributed representations of semantic features (e.g., how the features {furry}, {barking}, and {loyal} become experienced as the concept "DOG").

2.1. Modality-Independent Semantics

When PET and (later) fMRI methodologies became widely available in the late 1980s and early 1990s, one primary goal of cognitive neuroscientists interested in semantic memory was identifying amodal semantic processing areas. That is to say, cognitive neuroscientists began by trying to find areas that could be associated with the semantics "box" in cognitive box and line models, such as the "Content System" box and "Semantic Attributes" line in the classic Logogen model (Morton, 1969), the (unimplemented) "Meaning" ellipse in the influential Parallel-Distributed Processing (PDP) model (Seidenberg & McClelland, 1989), or the (again, unimplemented) "Semantic System" box in the Dual-Route Cascaded (DRC) model of word reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Hemodynamic imaging methods, which spatially localize neural activity by tracking accompanying changes in blood flow and blood oxygenation levels, offered the promise of being a window on semantics "in action," thereby allowing a determination of which brain areas are ubiquitously involved in the processing of meaning in the normally functioning human brain.

One of the first PET studies of word processing (Petersen, Fox, Posner, Mintun, & Raichle, 1988) began in this vein by contrasting activations in response to a semantic generation task to those in response to speaking words aloud. Importantly, both the semantic generation task and the speaking task were performed with cue words presented in both the visual and auditory modalities, so that regions more active in the semantic task regardless of presentation modality could be identified. The left inferior prefrontal cortex and the anterior cingulate cortex (especially the inferior anterior cingulate), both met the joint criteria of being more active in the semantic task than in the reading aloud task and of being active when task cues were presented in both the auditory and visual modality.

Many PET and fMRI studies that followed this original, ground-breaking one eventually came to a consensus that a broad network of areas, including the left inferior prefrontal cortex, the posterior temporal cortex, and more anterior regions of the temporal lobe are all involved in semantic processing (e.g., Demonet et al., 1992; Petersen et al., 1989; Pugh et al., 1996; Shaywitz et al., 1995), even in the absence of an explicit semantic task (i.e., during the incidental semantic processing that occurs while performing any task with orthographic stimuli; Price, Wise, & Frackowiak, 1996). This proposed network, derived from the study of normal adults, roughly corresponds to areas that had already been identified as critical to semantic processing based on patient studies dating back to the 1800s (Dejerine, 1892; Geschwind, 1967; Whitehouse, Caramazza, & Zurif, 1978). The correspondence between the two approaches is not expected to be perfect, as neuroimaging identifies brain areas that are *involved in* the processing of meaning whereas neuropsychology picks out in particular those that are most *necessary for* normal semantic functioning. However, taken together, neuropsychological and neuroimaging data suggest that semantic processing depends, at least in part, on the involvement of frontal and temporal lobe areas that are able to process information from multiple sensory modalities.

2.2. Modality- and Category-Dependent Semantics

In addition to identifying areas involved in the general, modality-independent processing of meaning-related information, neuroimaging studies have sought converging evidence for the kind of category-dependent processing deficits that have sometimes been implicated in studies of lesion patients. These include distinctions between the areas involved in the semantic processing of living things versus inanimate objects (Warrington & Shallice, 1984), tools versus other types of objects (Warrington & McCarthy, 1987), content versus function words (Benson, 1979; Caramazza & Berndt, 1985), nouns versus verbs (Damasio & Tranel, 1993), and concrete versus abstract words (Warrington, 1981).

Like neuropsychological studies, neuroimaging studies have identified patterns of activation that differ for different types of meaningful inputs, although these patterns are not always consistent across studies and their significance has been disputed (Devlin et al., 2002; Thompson-Schill et al., 1999). In at least some cases, brain areas associated with particular types of processing deficits in patients have also been found to show modality- or category-dependent patterns of activation in neuroimaging studies. For example, a study explicitly comparing lesion locations for patients impaired in the naming of people, animals, and tools to PET activations observed in brain-intact adults naming the same objects found a number of correspondences (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996). Overlapping areas in the anterior temporal cortex were associated with the naming of people, whereas more posterior temporal regions were associated in both groups with naming animals. Similarly, the lesions causing deficits to naming tools were also in the areas active while healthy participants named tools in the scanner. The study can also be taken as support for a more general distinction between the areas involved in processing living and nonliving things, as the activations observed in response to naming living things (people, animals) were always more anterior than those in response to naming nonliving things (tools).

Another example of correspondence between neuropsychology and neuroimaging comes from a PET study that examined the areas active in normal adults during the generation of colors or actions associated with an object (e.g., the color "red" or the action "drive" in association with an achromatic drawing of a stop sign; Martin, Haxby, Lalonde, & Wiggs, 1995). Left-lateralized fusiform gyrus activity was observed in response to the generation of color but not action words, in accordance with neuropsychological studies indicating that color blindness can be the result of fusiform gyrus damage (Zeki, 1990). Generation of action but not color words involved activity in the left inferior frontal lobe, in accordance with neuropsychological studies indicating that left frontotemporal damage can result in an impairment of verb processing (e.g., Caramazza & Hillis, 1991).

The identification of brain areas that seem to be involved in meaning processing only for particular types of input raises several questions. First, why should any such areas exist at all, rather than all semantic processing being accomplished by amodal processing areas, as many psychological models have assumed? Second, why are dissociations observed for some distinctions (e.g., living versus nonliving things) but not others (e.g., round objects versus triangular ones, or red objects as opposed to yellow ones)? Finally, one might ask what principles underlie the observed neural pattern—that is, for example, why are posterior temporal areas but not inferior frontal ones involved in the processing of tools? An appealing theory for addressing these questions is that the organization of conceptual information in the brain is driven by the perceptual and motor areas that become active during the encoding of that concept's meaning (e.g., Barsalou, Simmons, Barbey, & Wilson, 2003; Damasio, 1989; Pulvermuller, 1999; Shallice, 1988).

For example, under the Hebbian theory proposed by Pulvermüller (1999), the neural representation of a word has two parts: the form part, localized to classical language areas in the left perisylvian cortex and representing information such as the pronunciation of the word, and the conceptual part, localized to brain areas that were active during the encoding of the associated form part's semantics. This account provides an explanation of both why modality- and input-type-dependent semantic processing areas exist and also why they exist in the particular areas to which they have been localized (and not others). For example, according to this type of theory, the semantic representation of words that are learned primarily by co-occurrence of a particular phonological or orthographic form with a particular class of visual inputs will include high level visual cortices, because high level visual cortices become active coincidently with the verbal label (e.g., if SL points at her dog and says to KDF's young daughter "Shih-tzu," KDF's daughter will process the visual form of the shih-tzu coincidentally with hearing "Shih-tzu."). Similarly, the semantic representation of action verbs might involve motor cortices because learning what the word "jump" means often involves seeing or imagining others jump, or jumping oneself. Explanations of this type have been put forward for all of the category-based distinctions described thus far (see Pulvermuller, 1999, for an extensive discussion), although arguments against this view have also been levied (e.g., Caramazza & Mahon, 2003; Caramazza & Shelton, 1998, 1999).

2.3. Distributed Semantics and the "Binding Problem"

Theories that explain the organization of conceptual information in the brain via links between conceptual and sensory–motor processing differ in whether they view sensory and motor areas as the actual locus of semantic representations (the multiple semantic systems view of, e.g., Shallice, 1988) or as participants in conceptual processing, which arises as an emergent property of activity distributed across sensory–motor and association areas (e.g., Damasio, 1989). Other views of how the functional subcomponents of semantics are divided over brain areas have also been put forward, such as the Organized Unitary Content Hypothesis (Caramazza, Hillis, Rapp, & Romani, 1990) or the Conceptual Structure Account (Taylor, Moss, & Tyler, 2007). Despite important differences across these views, a critical similarity is that all acknowledge that semantic processing engages a sizeable network of neural areas, including the left inferior prefrontal cortex, anterior and posterior temporal lobes, and tempo-parietal areas (Price, 2000; for reviews, see Martin, 2007; Thompson-Schill, 2003). As will be the focus of the remainder of the chapter, it seems critical to understand how information in this neurally and (under most accounts) functionally distributed system comes to be reliably integrated to yield the subjective experience of unified concepts (associated with particular verbal labels) and how the organization of featural information in subsystems or subparts of the system ultimately yields conceptual-level organization.

This "binding problem" is a particularly difficult one because the human conceptual system displays a remarkable combination of both stability and flexibility. Experienced language users are able to rapidly and consistently map tens of thousands of arbitrary word forms (from multiple modalities, in the case of literate language users) onto concepts. Yet, the exact configuration of conceptual features accessed for a given word—even an unambiguous one, let alone a homographic or homophonous one—seems to be highly affected by context. For example, although a "moving" context might highlight the weight of a piano and tend to emphasize its similarity to other types of furniture, a "symphony" context might highlight the function of a piano and thus tend to emphasize its similarity to other types of musical instruments (e.g., Barclay, Bransford, Franks, McCarrel, & Nitsch, 1974; Tabossi & Johnson-Laird, 1980). Along the same lines, although across cultures, individuals, and time there is a considerable degree of consistency in the concepts that are considered to be "good" representatives of their categories (so-called "typicality effects" as described by Rosch, 1973, and Rips, Shoben, and Smith, 1973), these similarity structures can also be readily altered by context. For example, while out of context "robin" is considered a more typical bird than "chicken," after reading a sentence like "The bird walked across the barnyard," the word "chicken" is rated as more typical (and responded to more quickly) than is "robin" (Roth & Shoben, 1983).

Finally, while many conceptual categories seem to have a nearly universal existence and structure (as predicted by theories that attribute the driving principles for category structure to the organization of the human brain), it is also the case that people are quite proficient at creating novel (*ad hoc*) categories to meet particular goals—for instance, "things to pack in a small suitcase on a trip to London" (Barsalou, 1983). Thus, even as there seems to be reproducible structure to categories, there also seems to be flexibility and variability in the details of these structures over contexts, experiences, and individuals. This makes it unlikely that integration in the distributed semantic system is accomplished in a hard-wired fashion. Instead, what is needed is a means of linking spatially distributed information together in a manner that can be both reliable and stable, but also flexible. That critical ingredient may be time.

3. Electrophysiology and the N400

Whereas imaging techniques that track blood flow or blood oxygenation levels, such as PET or fMRI, can provide reliable information about the spatial location of neural activity, they afford relatively poor information about the timing of that activity, in part because such hemodynamic changes simply do not track neural activity on a millisecond level. Information about timing can be obtained, instead, from techniques that directly measure neural electrical activity. Neural communication takes place via current flow that generates an electrical potential in the conductive media inside and outside of neurons. The electrical potentials of a large number of these neurons that are arranged in a systematic fashion and activated in synchrony—conditions that seem to hold for cortical pyramidal cells, among others—will summate to create a signal large enough to be measured with electrodes placed on the scalp (e.g., Kutas & Dale, 1997). The continuous, rhythmic electrical activity of the brain as measured from the scalp is known as the electroencephalogram or EEG. Embedded within this signal are small, transient voltage fluctuations associated with perceptual, emotional, cognitive, and response-related processing elicited by specific events, such as the impingement of a stimulus on the sensory receptors.

To capture the brain activity associated with events of interest, where an "event" is broadly defined and could reflect, for example, even the absence of an expected stimulus, event-related potentials (ERPs) can be derived by extracting portions of the EEG activity that are time-locked to those events—often, stimulus onset or a behavioral or motor response. A number of these extracted segments are averaged together so that temporally specific activity (signal) can be distinguished from temporally nonspecific activity (noise). The resulting waveforms, one for each recording channel and each condition of interest, reflect voltage fluctuations over time either following or, in some cases, preceding the triggering event. Changes in the timing, amplitude, and scalp distribution of the ERP as a function of experimental manipulations can then be used to make inferences about neural and cognitive aspects of processing (e.g., Munte, Urbach, Duzel, & Kutas, 2000).

3.1. The N400 Component

A particular part of the ERP signal, sometimes called a "component" of the ERP, has been specifically associated with the processing of semantic information. The N400—so-called because it is a negative-going voltage fluctuation that tends to peak around 400 ms after stimulus-onset—was first observed in response to words that were semantically anomalous in their sentence contexts (e.g., "He spread the warm bread with socks"; Kutas & Hillyard, 1980b). Kutas and Hillyard anticipated that these anomalous words would elicit a P300, a positive-going ERP component that had been broadly linked to the processing of unexpected events of a wide variety of types (e.g., Duncan-Johnson & Donchin, 1977; Ruchkin, Sutton, & Tueting, 1975). Instead, they observed a larger negativity to the semantically unexpected, as compared with the expected, sentence endings. Figure 1 shows an example. However, words that were unexpected for other reasons—for example, because they appeared in an unexpected size—did elicit the anticipated P300 response (Kutas & Hillyard, 1980a). This was thus the first hint that the brain treats manipulations that impact meaning differently from those that do not.

Subsequent research has established that the N400 is not actually a marker for semantic unexpectedness as such. Instead, the N400 seems to

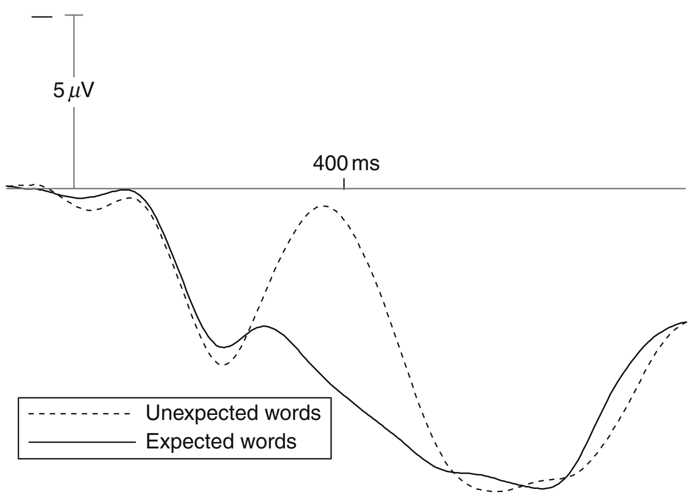

Figure 1 N400 sentential congruency effect. N400 responses are reduced in amplitude for words that are expected in a sentence context relative to those that are not. Thus, for example, the word "dog" elicits smaller mean amplitude responses between 250 and 500 ms poststimulus onset than does the word "sugar" as a completion for the sentence context "I take my coffee with cream and . . . ." In this and all subsequent figures, responses are shown at a middle, centro-posterior channel, with negative voltage plotted up.

be part of the normal response to potentially meaningful stimuli. In some respects, the N400 resembles the "sensory" ERP components that generally precede it in time. These components are obligatorily elicited by the apprehension of a stimulus in a particular modality (a different pattern of sensory components characterizes the response to stimuli in each modality; for a review, see Munte et al., 2000), and their characteristics (amplitude, latency, and distribution) are largely controlled by the physical properties of that eliciting event. The elicitation of the N400 seems similarly obligatory, but less yoked to sensory processing, as N400s are observed to meaningful stimuli across modalities. In other respects, the N400 is also similar to more "cognitive" components, which generally occur later in time and are fairly modality-independent. Cognitive components are highly affected by the information processing demands placed upon the person by the task environment. Thus, in different task environments, the same stimulus may elicit a very different response pattern on these components, and, indeed, such components can even be elicited in the absence of an external triggering event, if that absence is informative (e.g., Ruchkin et al., 1975). The N400 shares at least one characteristic with this type of component, in that it is strongly affected by the contextual setting of an eliciting stimulus (e.g., the same word presented in a list or as a sentence completion can elicit very different N400s).

N400s are thus an interesting blend of ERP component "types." As will be discussed in more detail, N400s are elicited and modulated by stimuli of a wide variety of types in all modalities. However, not all stimuli elicit clear N400 activity; those that do tend to be associated with meaning, such as words and pictures (e.g., Ganis, Kutas, & Sereno, 1996; Kutas, Neville, & Holcomb, 1987). Such stimuli elicit N400s even when they are processed incidentally and/or with little conscious awareness, as during some stages of sleep (Brualla, Romero, Serrano, & Valdizan, 1998), with masking (Deacon, Hewitt, Yang, & Nagata, 2000; Kiefer, 2002; Misra & Holcomb, 2003), or during the attentional blink (Rolke, Heil, Streb, & Hennighausen, 2001; Vogel, Luck, & Shapiro, 1998). The amplitude (but not the latency) of the N400 to these stimuli is modulated, not by the kind of perceptual parameters that tend to affect sensory components, but by factors specifically related to the ease of semantic processing for these stimuli (for a review, see Kutas & Federmeier, 2000). Manipulations of physical and linguistic variables that do not affect meaning (such as grammatical errors; Kutas & Hillyard, 1983) do not modulate the N400, and N400 effects are also not seen to unexpected events in other structured domains, such as music (e.g., Besson, Faieta, Peretz, Bonnel, & Requin, 1998). Thus, the N400 seems to be functionally specific to the processing of meaning, and, as described next, a large body of research points to the N400 as an electrophysiological marker of processing in the distributed semantic memory system.

3.2. Neural Loci of the N400

If the N400 reflects processing in semantic memory, then its neural origins would be expected to line up with the brain areas highlighted by functional imaging and neuropsychological studies. The N400 has a wide scalp distribution; it can be seen at most scalp sites, although it tends to be largest over the center of the head. This pattern would tend to implicate a distributed source, and, in fact, attempts to model the electrophysiological data have pointed to a wide-spread collection of cortical sources (Haan, Streb, Bien, & Rosler, 2000). However, the inverse problem—that is, attempting to determine the neural sources responsible for a particular scalp pattern—is mathematically ill-defined and is particularly difficult to even approximate for multifaceted, diffuse sources, as the N400 seems to be. Therefore, researchers have turned to other techniques, such as the use of intracranial recordings, which measure electrophysiological signals from electrodes placed on the surface of the cortex or implanted within it, or the measurement of the magnetoencephalogram (MEG) or the event-related optical signal (EROS), which each also track correlates of brain electrical activity with high temporal resolution but provide better spatial sampling.

A number of MEG studies (e.g., Halgren et al., 2002; Helenius & Salmelin, 2002; Helenius, Salmelin, Service, & Connolly, 1998, 1999; Kwon et al., 2005; Pylkkanen & McElree, 2007; Simos, Basile, & Papanicolaou, 1997; Uusvuori, Parviainen, Inkinen, & Salmelin, 2008) and one EROS study (Tse et al., 2007) have attempted to localize the activity responsible for the N400. These studies have fairly consistently pointed to sources in the superior/middle temporal gyrus, the temporoparietal junction, and the medial temporal lobe. Dorsolateral frontal cortical regions have also been implicated in some studies (Helenius et al., 1998). Although several of these studies have recorded only over the left hemisphere, studies that have recorded activity from both hemispheres have tended to find bilateral activity (consistent with growing data pointing to an important role for the right hemisphere in meaning processing; see, e.g., the review by Federmeier, Wlotko, and Meyer, 2008), although the right hemisphere source is often found to be weaker. Thus the same network of brain areas that have been implicated in amodal semantic processing by imaging studies seem to be an important part of the source of scalp-recorded N400 activity.

MEG and EROS studies can provide information not only about the source of brain electrical activity associated with semantic processing but also its timecourse. Halgren et al.'s (2002) data, for example, suggest that the scalp-recorded N400 reflects a wave of activity beginning around 250 ms after-onset in the posterior half of the left superior temporal gyrus, spreading forward and ventrally to encompass most of the left temporal lobe by 365 ms, and then spreading to the anterior temporal lobe in the right hemisphere and to the frontal lobe bilaterally by the peak of the N400 response (between 370 and 500 ms). The only EROS N400 study (Tse et al., 2007) found a similar progression of activity from the superior temporal lobe to frontal areas and then back again. These findings are complemented by work using intracranial recordings, typically from patients undergoing preoperative evaluation for epilepsy surgery. Whereas deep cortical sources may be difficult to see with EROS and MEG (because of various physical limitations on the signal strength), intracranial data in N400-eliciting paradigms have typically been collected from the medial and inferior temporal lobe (where epileptic sources are most frequent). Intracranial studies have identified a source in the anterior medial temporal lobe that patterns closely with the scalp-recorded N400 in its sensitivity to semantic priming, semantic anomaly, repetition, and verbal memory (Elger et al., 1997; Fernandez et al., 2001; Guillem, N'Kaoua, Rougier, & Claverie, 1996; Halgren, Baudena, Heit, Clarke, Marinkovic, Chauvel, et al., 1994; Halgren, Baudena, Heit, Clarke, Marinkovic, & Clarke, 1994; McCarthy, Nobre, Bentin, & Spencer, 1995; Nobre, Allison, & McCarthy, 1994; Nobre & McCarthy, 1994; Smith, Stapleton, & Halgren, 1986). N400-like activity has also been observed in intracranial recordings from a number of other brain areas, including the middle and superior temporal areas picked out by MEG/EROS, and inferior temporal and prefrontal cortical areas. The spatial information available from intracranial recordings is limited by the fact that relatively few recording sites can be sampled in any individual (and because the placement of those sites is determined by clinical rather than research concerns). However, data across such studies suggest that the N400 reflects activity in a distributed set of brain regions, including higher order perceptual areas, multimodal processing areas, and even emotion- and motivation-related areas, such as the amygdala. These areas all show activity over a similar time span, between about 250 and 500 ms after stimulus onset.

If the N400 reflects activity in an amodal (or multimodal) semantic system, then such activity should be seen in response to the full range of stimuli that are associated with meaning. And, in fact, N400s have been recorded to all types of linguistic stimuli, including spoken, written, and signed words, and word-like items such as pronounceable pseudowords (e.g., pank) and familiar acronyms (e.g., VCR) (Holcomb & Neville, 1990; Kutas et al., 1987; Laszlo & Federmeier, 2008). N400s are also observed to meaningful but nonlinguistic stimuli such as environmental sounds (e.g., animal sounds, telephone ringing; Chao, Nielsen-Bohlman, & Knight, 1995; Van Petten & Rheinfelder, 1995), line drawings and scenes (Ganis & Kutas, 2003; Ganis et al., 1996; Nigam, Hoffman, & Simons, 1992), faces (Barrett & Rugg, 1989; Bobes, Valdes-Sosa, & Olivares, 1994), movies (Sitnikova, Kuperberg, & Holcomb, 2003), and gestures (Kelly, Kravitz, & Hopkins, 2004; Wu & Coulson, 2005). Another important aspect of the modality-independence of the N400 response is that N400 amplitudes are modulated by semantic relationships between stimuli, irrespective of stimulus modality or type. That is, the N400 response to a picture, for example, can be affected not only by its semantic relationship with another picture (Barrett & Rugg, 1990b; McPherson & Holcomb, 1999), but also with a visually presented word or sentence (Federmeier & Kutas, 2002; Wicha, Moreno, & Kutas, 2003), an auditory word (Pratarelli, 1994) or even a smell (Grigor, Van Toller, Behan, & Richardson, 1999; Sarfarazi, Cave, Richardson, Behan, & Sedgwick, 1999). Such cross-modal effects are sometimes weaker than corresponding within-modality ones (Anderson & Holcomb, 1995) but persist even when stimuli are masked to reduce the contribution of strategic, attentionally driven processing (Eddy, Schmid, & Holcomb, 2006; Kiyonaga, Grainger, Midgley, & Holcomb, 2007). Thus, the N400 seems to occur at a processing stage that is common across sensory modality and stimulus type.

On the other hand, if the semantic system contains modality-dependent as well as modality-independent processing areas, then the source of the N400 might be expected to shift for different kinds of inputs or different kinds of words. In fact, there are reliable differences in the scalp distribution of the N400 elicited by different types of stimuli. N400s to visually presented words have a medial, centro-posterior focus and are often larger over the right than the left hemisphere (which should not be taken to suggest greater involvement from the right hemisphere, as, depending on the precise orientation of the electrical dipole, a left hemisphere source can elicit electrical activity with a maxima over right hemisphere electrode sites) (Kutas & Hillyard, 1982). N400s to auditory words, instead, manifest a more central scalp distribution (Holcomb & Anderson, 1993; McCallum, Farmer, & Pocock, 1984). Environmental sounds elicit a scalp distribution similar to that seen for auditory words, but with a different pattern of hemispheric asymmetry. This is consistent with views that posit a left hemisphere bias for the processing of verbal stimuli but a right hemisphere bias for the processing of nonverbal stimuli (Van Petten & Rheinfelder, 1995). N400 responses to pictures and scenes are notably more anterior than those to visually presented words (Ganis et al., 1996; Holcomb & McPherson, 1994), perhaps reflecting enhanced contributions from brain areas involved in visual- or imagery-related processing. Interestingly, a similar anterior shift is seen for the N400 responses to concrete, as compared with abstract, words (Holcomb, Kounios, Anderson, & West, 1999; Kounios & Holcomb, 1994; Lee & Federmeier, 2008). Although the precise nature of these distributional differences is not entirely understood, their existence suggests that semantic processing samples from partially nonoverlapping sets of neural areas for different types of stimuli (and may therefore be functionally nonidentical as well; see, e.g., Federmeier & Kutas, 2001), consistent with the Hebbian cell-assembly type of accounts of semantics that have already been discussed.

3.3. The N400 and Conceptual Structure and Flexibility

If the N400 is a marker of processing in semantic memory, then it should reflect the kind of conceptual-level structure uncovered in behavioral studies. The N400 is sensitive to the taxonomic organization of knowledge, as can be seen in ERP studies of sentence verification (with smaller N400s to "animals" than "furniture" in "All dogs are animals/furniture"; Fischler, Bloom, Childers, Roucos, & Perry, 1983). The N400 is also sensitive to category membership in a manner graded by typicality (Figure 2), with greater facilitation (amplitude reduction) for more than less typical category members following a category label cue (e.g., smaller N400s in response to "Collie" than "Bichon Frise" after the cue "DOG"; Harbin, Marsh, & Harvey, 1984; Heinze, Muente, & Kutas, 1998; Polich, 1985; Stuss, Picton, & Cerri, 1988). More generally, N400 amplitudes are modulated by semantic similarity of many types between stimuli, including shared physical, functional, affective, and cognitive features (e.g., Barrett & Rugg, 1990a,b; Bentin, McCarthy, & Wood, 1985; Holcomb & Neville, 1990; Kellenbach, Wijers, & Mulder, 2000; Zhang, Lawson, Guo, & Jiang, 2006). This sensitivity arises not only when participants are directed to notice or judge similarity or categorical relations, but also under more implicit conditions. For example, during sentence processing (when participants simply read for comprehension without any overt behavioral task), categorical

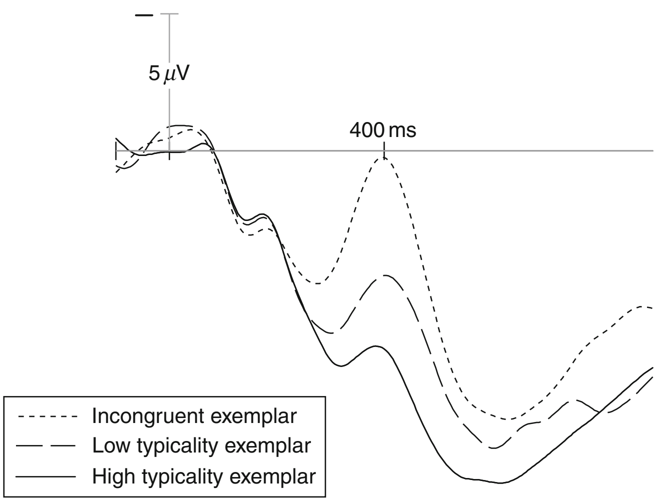

Figure 2 N400 category typicality effects. In response to a category label cue, such as "A type of fruit," N400 responses are reduced in amplitude to category members (e.g., "apple" or "cherry") relative to nonmembers (e.g., "penny") and are more reduced to high typicality (e.g., "apple") than to low typicality (e.g., "cherry") category exemplars.

similarity to an expected ending produces N400 facilitation for even contextually anomalous sentence completions (e.g., "He caught the pass and scored another touchdown. There was nothing he enjoyed more than a good game of baseball"; Federmeier & Kutas, 1999, 2001). Thus, even when semantic relationships are irrelevant for a particular task situation, N400 processing seems to be influenced by the structure of conceptual knowledge. Finally, N400 effects can be observed even for newly learned categories, with smaller N400s to novel exemplars that share more features in common with the training set (Gratton, Evans, & Federmeier, 2009).

Because the N400 is assumed to reflect active processing in semantic memory, it should also be sensitive to dynamic properties of information use—that is, to factors such as the frequency and recency with which conceptual information has been accessed and to the context in which a meaningful item occurs or has occurred in the past. As can be seen in Figure 3, N400 amplitudes are indeed affected by word frequency, with smaller (facilitated) N400 responses to high than to low frequency words (Muente et al., 2001; Rugg, 1990; Van Petten & Kutas, 1990). As Figure 3 shows, the N400 is also sensitive to repetition (Rugg, 1985; Van Petten, Kutas, Kluender, Mitchiner, & McIsaac, 1991) and is modulated by recognition memory (Chao et al., 1995; Friedman, 1990; Smith et al., 1986). Furthermore, such effects of memory on the N400 are preserved in amnesic patients (Olichney et al., 2000), who are impaired in episodic—but not semantic—memory. Finally, the N400 is highly sensitive to context; indeed, one of the most important uses of the N400 as a measure has been in studies of context effects in language. N400 amplitudes are modulated by

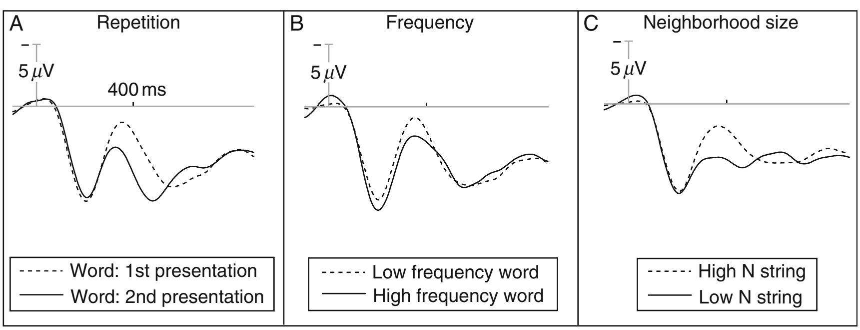

Figure 3 Effects of repetition, frequency, and orthographic neighborhood size on the N400. In (A), the N400 elicited by the second presentation of a word in a list format is smaller than that to the first presentation. In (B), higher frequency words elicit smaller N400s than lower frequency words. In (C), meaningless strings with high orthographic neighborhood size elicit larger N400s than those with low orthographic neighborhood size. These factors, along with semantic congruency, comprise the most important determinants of N400 amplitude.

the fit of a meaningful item to its context, whether that context is a single word or picture, or a sentence, discourse, or movie (for verbal contexts, see review by Kutas & Federmeier, 2000; for nonverbal contexts, see, e.g., West & Holcomb, 2002; Sitnikova et al., 2003). Context effects on the N400 are graded, with the amplitude of the N400 showing a strong negative correlation with measures of contextual fit, such as ''cloze probability'' (the percentage of people who would choose to complete a given sentence fragment with a particular word; Taylor, 1953). Thus, the N400 indexes both the structure and the flexibility that behavioral studies of conceptual processing have highlighted.

3.4. The N400: A Neural Marker of Processing in Semantic Memory

In sum, the N400 has all of the properties one would expect of a marker of neural activity associated with semantic memory. It reflects activity in a distributed, multimodal set of brain areas. This activity seems to be fairly automatically elicited in response to a wide variety of types of meaningful stimuli. Furthermore, the functional sensitivity of activity in this network conforms to both the kind of stability and flexibility expected of conceptual-level processing, showing influences of similarity, typicality, recency, frequency, and context. With such a marker, then, it becomes possible to address core, outstanding questions about processing in semantic memory, such as what types of inputs become linked up to meaning and how, and what constraints govern the binding of information into conceptual-level representations.

4. From Input to Meaning

Our sensory receptors are constantly bombarded with information, not all of which is meaningful in nature. This raises the question of which stimuli are ultimately selected for semantic processing, and how and when that selection takes place. A review of the N400 literature suggests an initial answer to this question, as, indeed, not all types of stimuli seem to elicit N400 responses. In particular, whereas, for example, visually presented words elicit clear N400s, strings of letters that do not follow the typical spelling conventions of a language (''illegal strings''; e.g., XQF) do not elicit visible N400 activity when presented in unconnected lists (e.g., Laszlo & Federmeier, 2007; Rugg & Nagy, 1987). Interestingly, pronounceable pseudowords (orthographically regular nonwords, such as GORK) do elicit N400s (and show N400 repetition effects) in unconnected lists (e.g., Laszlo & Federmeier, 2007; Rugg & Nagy, 1987), despite also being novel stimuli.

This is typically explained by the fact that, although pseudowords are not themselves familiar items, they contain many "word-like" subcomponents and are thus similar to many familiar, meaningful items (e.g., GORK is an orthographic neighbor of—that is, shares all but one letter in common with—FORK and WORK and GORE, etc.). A similar pattern has been seen for pictures (Penney, Mecklinger, & Nessler, 2001), with reduced N400s to repetitions of unfamiliar but possible objects (similar to that seen for familiar pictures; Eddy et al., 2006) but not to structurally impossible objects.

This pattern of N400 effects has been interpreted as indicating that access to the semantic system may be "gated" in a bottom-up fashion by some property of perceptual inputs that makes them likely to be associated with information in long-term memory. Hypotheses about what that gating property is likely to be and when in processing it might apply differ depending on the type of underlying model of recognition that is assumed. The following discussion will focus on the recognition of visual words, since that has been fairly well studied with electrophysiological measures, although similar analyses could be done for semantic access in response to auditory words or for objects.

4.1. Models of Visual Word Recognition

The two most prevalent types of reading model in the current literature are those that are functionally homogenous and those that instead apply different computations at different levels of processing and to different types of items. The so-called "Triangle" model (Harm & Seidenberg, 2004), designed to simulate the mapping of orthography to semantics, is a prominent example from the functionally homogenous modeling tradition. It represents orthography, phonology, and semantics in a fully interactive manner, using a uniform set of computational principles. In contrast, the most recent iteration of the so-called nested modeling tradition, the Connectionist Dual Process Plus (CDP+) model (Perry, Ziegler, & Zorzi, 2007), focuses on linking orthography with phonology. Although the CDP+ model is also connectionist, it uses serial rather than parallel processing at some of its levels of representation. Also, critically, the CDP+ model and other models in its tradition are functionally heterogeneous, in that the computations that are most likely to produce the correct pronunciation in response to items with irregular spelling-sound correspondence (e.g., YACHT) are separable from those for items with regular spelling-sound correspondence (e.g., SHIP).

In fact, the computational principles embodied in the Triangle and CDP+ models mirror the theoretical constructs of a long-standing, primary debate in the reading literature. This debate centers on whether or not it is necessary to have two functionally (and presumably neurally) separable systems in order to account for the ability of fluent readers (at least of

English) to read aloud both pseudowords and orthographically irregular words. Because they are novel, pseudowords presumably cannot be processed by "looking up" their phonological representation in a stored database of meaningful items (i.e., a "lexicon"), apparently necessitating a system of orthography-to-phonology translation rules to explain the ability to pronounce them. The correct pronunciation of orthographically irregular words, on the other hand, could not be obtained through the application of those same translation rules, suggesting the need for a direct associative system in which orthography is linked to stored information about the word's pronunciation and meaning. This dissociation of systems is supported by patterns of deficits observed in dyslexia, with some patients impaired selectively in the reading of legal nonwords, as in phonological dyslexia (e.g., Patient LB; Derouesne & Beauvois, 1985), and others, instead, impaired selectively in the reading of illegal words, as in surface dyslexia (e.g., Patient MP; Patterson & Behrmann, 1997).

The model that best typifies theories of word reading that include both a directly associative path for illegal words and a rule-based translation for pronounceable nonwords is the influential Dual-Route Cascaded (DRC) model of word reading (Coltheart et al., 2001, also a previous increment of the CDP+ model). So-called "dual-route" systems directly map the orthography of words with irregular spelling-sound correspondence onto their associated phonology (and thence onto semantics). Pseudowords, instead, are translated from orthography to phonology by the application of binary, serial spelling-to-sound rules. In such models, orthographic regularity thus serves as a critical gating factor, determining which of the two computationally and neurally differentiable pathways to meaning a given input can take.

In contrast, building on the massively interactive, computationally homogenous view of word processing originating with, for example, Seidenberg and McClelland (1989), a second class of reading models instead instantiates a functionally unified system, in which all inputs make contact with both phonological and semantic representations. In such models, the recognition of irregular words is often accomplished via activity that links orthography to semantics, which, in turn, solidifies phonological activation patterns. Pseudowords can be recognized using the same computational machinery by taking advantage of mappings between orthography and phonology developed through prior experience with words containing similar parts; for example, the network is able to learn that word-initial K is often pronounced /k/ and that word-final AT is often pronounced /æt/, and is therefore able to produce the normatively correct pronunciation /kæt/, when given the input KAT, without ever having seen that token before.

Though the computations performed to successfully process orthographically irregular words and pronounceable nonwords are not identical even in models of this tradition, they are functionally homogenous in that the same class of computations is performed on every input. Unlike dual-route models, therefore, homogenous models do not assign any special status to orthographic regularity as a gating factor for word recognition. Indeed, the idea that there is *any* such gating factor is somewhat incompatible with these types of reading models, as it implies that some orthographic inputs undergo different computations than others.

4.2. Constraints on the Mapping of Inputs to Semantics?

Given that the two types of reading models make different predictions about when and how different classes of inputs become associated with semantics, the N400 would seem a useful measure for deciding between these accounts of word recognition. Surprisingly, although some electrophysiological work has pointed to orthographic regularity as a filter on N400 processing (e.g., Deacon, Dynowska, Ritter, & Grose-Fifer, 2004), few parallels have been drawn between questions in the modeling literature about what type of computations different input classes undergo and questions in the electrophysiological literature about what factors affect the presence and size of the N400 response to those same input classes. We therefore set out to specifically test models of reading by examining the independent contributions of factors like orthographic regularity and stimulus familiarity to semantic processing, as indexed by the N400 (Laszlo & Federmeier, 2007, 2008, in press).

We first examined whether or not orthographic regularity gates semantic access (as had been previously suggested by Deacon et al., 2004) by comparing N400 responses to words, pronounceable pseudowords, unfamiliar illegal strings, and—a novel stimulus class for this literature—orthographically illegal but familiar acronyms (e.g., DVD). As already described, N400 repetition effects (reduced amplitudes upon second presentation of the input) had been seen for words and pseudowords but not illegal strings (Rugg & Nagy, 1987). This pattern could be explained by assuming that access to semantics (as indexed by the N400) occurs only after the perceptual system filters stimuli based on orthographic regularity. However, there are also important differences in familiarity between these classes of items: words are obviously familiar; pseudowords are novel as whole items, but, by virtue of being orthographically regular, are also similar to many familiar items; unfamiliar illegal strings, in contrast, are neither familiar nor similar to familiar items. The inclusion of a familiar class of orthographically illegal items thus opens up a means of disentangling the contributions of familiarity and orthographic regularity to the observed pattern. Our hypothesis was that if orthographically regular and irregular items are processed separately, as suggested by dual-route models of reading, we would be able to observe differences in the N400 elicited in response to orthographically regular and irregular items matched for familiarity. In contrast, if orthographic regularity is not a critical gating factor, we expected to observe similar N400 responses to both orthographically illegal acronyms and familiar, regular words.

In fact, we found that familiar but orthographically illegal acronyms elicited N400 repetition effects that were identical in size, timing, and distribution to those observed for words and pseudowords (Laszlo & Federmeier, 2007; see Figure 4). The results thus suggested that all stimuli that are familiar or that contain familiar subcomponents elicit indistinguishable attempts at semantic access. This pattern supports functionally homogenous models over dual-route models that instead propose distinct processing pathways gated by orthographic regularity.

Our more recent work has suggested that not even familiarity is a necessary and sufficient prerequisite for the elicitation of an N400, implicating a view in which access to semantics is not gated by any specific perceptual (or linguistic) property of inputs. Even unfamiliar, orthographically illegal items will elicit clear N400 activity when they are presented as

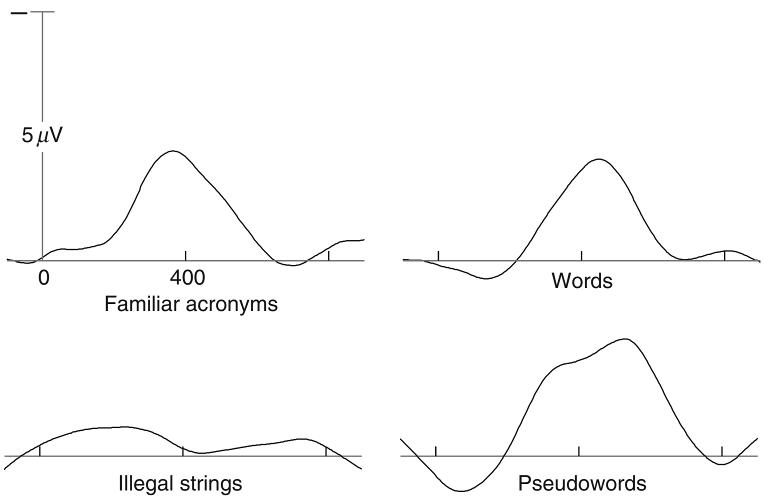

Figure 4 N400 repetition effects across stimulus types. N400s are reduced in amplitude when stimuli are repeated. Shown here are N400 repetition effects plotted as difference waves, which are computed using a point-by-point subtraction of the waveform elicited by the second presentation of an item from the waveform elicited by the first presentation of that same item. Difference waves can therefore be conceptualized as a continuous time depiction of the effect of repetition. In this figure, repetition effects are shown for words (e.g., "DARK"), orthographically regular but unfamiliar pseudowords (e.g., "DAWK"), orthographically illegal but familiar acronyms (e.g., "DVD"), and orthographically illegal, unfamiliar strings (e.g., "NKL"). Whereas unfamiliar illegal strings fail to elicit N400 repetition effects, familiar illegal strings—acronyms—elicit N400 repetition effects that are identical in size, timing, and distribution across the scalp to those elicited by words and pseudowords. Thus, orthographic regularity is not a requirement for semantic access; instead the degree to which a stimulus is familiar or similar to familiar items seems to be more important.

completions of highly constrained sentences (e.g., "THEY SAW THE LIGHTNING AND HEARD THE NKL"; Laszlo & Federmeier, 2008). Furthermore, the N400s to these unfamiliar, illegal items are modulated in amplitude by the same kind of factors that modulate N400s to familiar and regular items, such as orthographic similarity to an expected completion (Laszlo & Federmeier, in press; see Figure 5). Thus, we have suggested that semantic processing is attempted for (and some level of N400 activity thus elicited by) all incoming orthographic stimuli, although the degree to which this semantic processing will be successful—that is, result in a coherent, replicable pattern of activity—will vary with factors such as the type and level of contextual support and (indeed) frequency, familiarity, regularity, and orthographic neighborhood size, among others. Thus, we do not propose that familiarity and regularity have no effect on N400 processing; we simply suggest that neither familiarity nor regularity is as critical to the elicitation of N400 processing as was once believed. Highly unfamiliar stimuli presented out of context may not elicit consistent enough activity patterns in semantic memory to, for example, show a benefit from repetition. However, when those same stimuli are encountered in rich contexts, they can be mapped onto the coherent semantics built from the context, allowing their processing to resemble that for familiar stimuli.

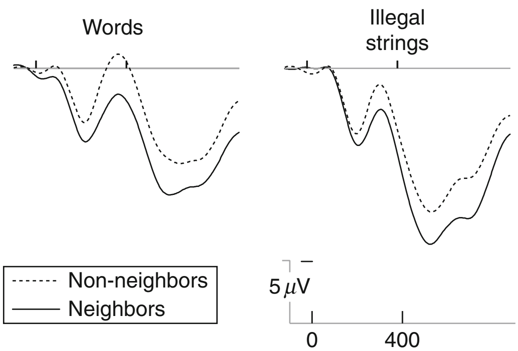

Figure 5 Orthographic neighborhood effects on the N400. Orthographic neighbors of expected, but never presented, sentence completions elicit smaller N400s than do orthographically unrelated completions. For example, given the sentence context "The genie was ready to grant his third and final . . . ," smaller N400 responses are observed to the contextually anomalous word "DISH," which is an orthographic neighbor of the expected completion "WISH," than to the equally anomalous, but orthographically unrelated word "CLAM." Although illegal strings elicit smaller N400 responses overall, the same effect holds for the comparison between strings that are orthographically related to the expected completion (e.g., "WXSH") and those that are not (e.g., "RQCK"). Thus, it seems clear that, at least in rich semantic contexts such as sentences, even unfamiliar, orthographically illegal strings can elicit N400 activity, which shows a similar functional sensitivity to that for familiar words.

Applying a meaning derived from context to an unfamiliar string is a highly adaptive action for the language comprehension system to take, as it would seem to be a good way to incidentally acquire the meanings of unfamiliar words or acronyms—a type of learning that occurs even for highly fluent readers throughout the lifespan. Indeed, this is exactly the mechanism for word learning assumed by computational theories of semantic acquisition that utilize latent semantic analysis (LSA; Landauer, Foltz, & Laham, 1998). Thus, although the assumption that some inputs are selected for semantic processing and others not has a certain degree of intuitive plausibility, especially based on models wherein semantic access is a discrete stage that follows perceptual analysis, our N400 data suggest instead that attempts to access semantic memory might constitute part of the normal, default response to sensory inputs of all types. Indeed, in the auditory modality, where incoming information is distributed over time, N400 responses and effects can be observed even before enough information to allow identification has accrued (Van Petten, Coulson, Rubin, Plante, & Parks, 1999). The view that attempts at semantic processing are obligatorily engaged for all inputs, regardless of any particular low-level linguistic property, is compatible with massively interactive models of language comprehension (Harm & Seidenberg, 2004) and also, more generally, with approaches that posit overlap in the computations (and brain areas) that underlie what have traditionally been divided into "perceptual" and "semantic" aspects of the processing of language (e.g., Barsalou et al., 2003; Pulvermuller, 1999; Shallice, 1988).

4.3. Meaning in Context

Semantic information can be derived from individual perceptual stimuli, such as words in an unconnected stream of text presented to unwitting experimental participants. However, it is perhaps more typical for meaningful stimuli to occur as part of more complex meaning structures—that is, for objects to appear in scenes, words in sentences, and sentences as parts of discourses. These higher level structures serve as contexts that can affect the perceived meaning of individual incoming stimuli, even as the individual stimuli, in turn, contribute to the overall, emergent meaning of the larger scale discourse. This interplay between individual inputs and context raises the question of how semantic information is integrated across stimuli and over time, and whether there are constraints on the levels or types of context that can shape the initial semantic processing of an input, as indexed by the N400.

It is well known that stimuli are easier to process if they occur in contexts that foreshadow aspects of their semantics, whether those contexts are other, individual stimuli (as in semantic priming) or larger meaning structures (as in sentence-level congruity effects). However, different mechanisms have sometimes been posited for facilitation arising from the semantic similarity of an input to an individual contextual element (e.g., a single word) and that arising from an input's fit into a higher level representation, such as the message-level meaning derived from a sentence or discourse (e.g., Forster, 1981; Seidenberg, Waters, Sanders, & Langer, 1984; see discussion in Van Petten, 1993b). The former type of facilitation is argued on some theories to arise from mechanisms, such as spreading activation, that occur rapidly and automatically (without attention). However, the semantic representations of higher order language structures cannot possibly all be held in memory, as there are an infinite number of possible sentences and discourses. Thus, facilitation from sentence and discourse contexts is assumed to occur through the application of attentionally controlled processes that integrate information across words and store those integrated representations in working memory.

Mirroring the pattern seen in behavioral measures, N400 responses are facilitated—that is, amplitudes reduced—as a function of the semantic fit between an item and information provided by an individual prior stimulus (Barrett & Rugg, 1990b; Bentin et al., 1985), a sentence or scene (Ganis & Kutas, 2003; Kutas & Hillyard, 1984), or a discourse or movie (Sitnikova et al., 2003; van Berkum, Hagoort, & Brown, 1999). As already described, semantic priming effects on the N400 can be seen even under conditions that reduce or eliminate attentional demands and the possibility of strategic processing (e.g., Brualla et al., 1998; Deacon et al., 2000; Vogel et al., 1998), thus suggesting that they could arise from automatic processes such as spreading activation. However, effects in sentences or discourses can be seen before the text has been concluded and, indeed, seem to build up incrementally (Van Petten & Kutas, 1990, 1991), in line with the hypothesis that these effects are tracking the availability of message-level information as context accrues. Importantly, when compared directly, word-level and higher level context effects on the N400 have been found to be similar in their functional sensitivity (e.g., modulation by contextual strength), as well as in their timing and scalp distribution (Kutas, 1993; Van Petten, 1993a). In at least some circumstances, simultaneous, joint influences of word-level and message-level context have been observed (Van Petten; Van Petten, Weckerly, McIsaac, & Kutas, 1997). Findings like these suggest that, if word and message level context effects do arise from different underlying mechanisms, those mechanisms nevertheless have a similar eventual impact on relatively early aspects of semantic access.

However, in addition to these similarities, there are also differences in how levels of context impact semantic processing, which are revealing of the relative strength and the nature of different information sources. As already discussed, N400 amplitudes are sensitive to factors that influence the relative ease with which meaning-related information can be gleaned from stimuli and, perhaps, also the amount of available information. Out of context, N400 amplitudes are smaller to frequent than to infrequent words and are reduced by factors, such as repetition, lexical associative priming (e.g., bee–honey), and semantic feature overlap (Koivisto & Revonsuo, 2001; Rugg, 1985, 1990; Van Petten & Kutas, 1990; Van Petten et al., 1991), which would be expected to ease meaning access. Smaller N400 amplitudes are also observed for words with low orthographic neighborhood densities (Holcomb, Grainger, & O'Rourke, 2002; Laszlo & Federmeier, 2007, 2008; see Figure 3). One explanation for this pattern is that information associated with all items that share a high level of overlap with an incoming stimulus tend to become active in parallel. Thus, when processing an input (e.g., "BANK") with many orthographic neighbors (e.g., "DANK," "SANK," "TANK," "BARK," "BUNK," "BAND," "BANG," etc.), features associated with all of the neighbors become active to some degree, leading to a high level of activity in the semantic system. However, when processing an input with a low neighborhood density (such as OWL, whose only neighbors are AWL, OIL, and OWN), a much lower overall activity level is elicited in the semantic system, leading to smaller N400s. A similar explanation has sometimes been put forward to explain smaller N400 amplitudes to words with abstract as opposed to concrete meaning features (Holcomb et al., 1999; Kounios & Holcomb, 1994). The presence of congruent, higher level context information, however, eradicates many—although not all—of these effects.

Word frequency effects, for instance, disappear fairly early on in the processing of sentences (Van Petten & Kutas, 1990). It is likely that N400 amplitudes to words out of context reflect baseline levels of activation, which are slightly higher for more frequent words. These baseline levels, however, are rapidly overridden by the activity induced as a meaningful sentence or discourse is processed. Similarly, although effects of lexical association and sentence-level congruity can be jointly observed on words in sentence-intermediate positions (when message-level constraints are still likely to be low to moderate; Van Petten, 1993a), by the ends of constraining sentences even lexical association effects from nearby words are negligible (Coulson, Federmeier, Van Petten, & Kutas, 2005; Van Petten, Coulson, Weckerly, et al., 1999). Concreteness effects on the N400 are also reduced or eliminated for words in sentence contexts (Holcomb et al., 1999). This set of data thus suggests that message-level semantic constraints often have a stronger and longer-lasting impact on semantic activation levels than do word-level ones.

However, higher level contexts do not merely provide a stronger source for facilitation than do word-level factors; they actually shape how word-level information is processed. Repetition, for example, generally facilitates the processing even of words embedded in sentences and discourses (Anderson & Holcomb, 2005; Besson, Kutas, & Van Petten, 1992; Van Petten et al., 1991), indicating that it is usually easier to re-access the semantic features associated with a given perceptual stimulus. However, such effects are quite sensitive to context (Besson & Kutas, 1993) and can be eliminated or even reversed (Camblin, Ledoux, Boudewyn, Gordon, & Swaab, 2007; Ledoux, Gordon, Camblin, & Swaab, 2007; Swaab, Camblin, & Gordon, 2004). This occurs, for example, when such repetitions are infelicitous, as in the following example: "At the office Daniel moved the cabinet because Daniel needed more room for the desk." This "repeated name penalty" seems to arise because information about previously mentioned discourse participants is somehow actively maintained in memory. Re-referencing, then, most felicitously occurs through a pronoun, which cues the system to use that already active information. Under those circumstances, repetition of a perceptual form creates processing difficulties, rather than facilitation, since the system initially assumes that a new participant is being introduced. More generally, this pattern emphasizes that the impact of lower-level "bottom-up" factors such as repetition seems to depend heavily on the current state of the semantic system, as created and maintained by context and other higher level factors.

Finally, there are stimulus-level effects that do not seem to be affected by higher level context information. Letter strings with low orthographic neighborhood density, such as "VCR," elicit much smaller N400 responses than do strings with more neighbors, such as "FORK" (Holcomb et al., 2002; Laszlo & Federmeier, 2007, 2008). This is true irrespective of the familiarity of those strings; indeed, with other factors held constant the N400 response to unfamiliar strings such as "NKH" (low density; very small N400 response) or "FUNT" (high density; more negative N400 response) is identical to that for highly familiar strings with the same orthographic neighborhood density, such as "VCR" or "FORK" (Laszlo & Federmeier, 2007, 2008). Moreover, this effect of orthographic neighborhood size seems to be unaffected by the availability of message-level information. The pattern seen in word lists, in which items with large orthographic neighborhoods elicit larger N400s than items with small orthographic neighborhoods (Laszlo & Federmeier, 2007), is also observed at the end of even highly constraining sentence contexts (Laszlo & Federmeier, 2008, in press). The notable difference in the effect of context on the impact of word frequency versus orthographic neighborhood size suggests that the former effect may arise due to activation states in semantic memory, which are more transient and malleable, whereas the latter effect may arise instead because of how information is organized. If access to the semantic system for visual word inputs occurs via representations that are organized by orthographic similarity, then neighborhood effects would be expected to be fairly ubiquitous. N400 patterns across contexts and tasks may thus help provide a means of determining which factors reflect aspects of information structure (e.g., orthographic similarity, semantic feature overlap) and which reflect the dynamics of information use.

5. Semantics "ON TIME"

Overall, then, the pattern across studies points to a semantic system that is shared across modality and stimulus type and that is modulated by information derived both from individual prior stimuli and from higher level structures that are built and maintained over time, as during the processing of a conversation, text, or movie. This system may not be best characterized as fully "amodal" in nature, given observed modality and stimulus-type effects on the scalp distribution of the N400 (and, by inference, the precise configuration of neural generators involved in semantic processing in these cases). However, the binding of meaning to input and between single inputs and context does not seem to be gated by specific perceptual properties or constrained to occur within a particular level or type of stimulus. The ubiquitous nature of semantic processing suggested by electrophysiological data, however, serves to reemphasize the question of how the semantic system can ensure that this diverse, distributed information is appropriately linked up and available when needed.

Although there do not seem to be strong stimulus type or context type constraints on access to the semantic system, electrophysiological data suggest that *time* may be a critical, gating factor for meaning processing. An oft-noted—but little discussed—fact about the N400 is its striking temporal stability. The N400 (to visually presented words) peaks around 375 ms poststimulus-onset in young adults (~20 years old; e.g., Kutas & Iragui, 1998). It is observed later in children (Holcomb, Coffey, & Neville, 1992), and its latency decreases with age and language experience to reach a minimum in early adulthood. Even in adulthood, language proficiency continues to impact N400 latency: in bilingual individuals, N400 responses peak later for the nondominant as compared with the dominant language (Ardal, Donald, Meuter, Muldrew, Luce, 1990; Moreno & Kutas, 2005). N400 latency then increases again after young adulthood at a rate of about 1.8–1.9 ms per year (Kutas & Iragui, 1998). Increased N400 latencies (relative to age-matched controls) have also been noted in conjunction with neurological or psychiatric disorders (e.g., schizophrenia: Grillon, Ameli, & Glazer, 1991; Koyama et al., 1991; Alzheimer's disease: Iragui, Kutas, & Salmon, 1996; Olichney et al., 2002). Thus, N400 latency clearly reflects something about the neurophysiological state of an individual, which is modulated by anatomical and physiological changes associated with experience, age, and disease.

However, within a given person of a particular age, experience level, and neurological condition, N400 latencies are remarkably resilient to manipulation by psychological factors of the type manipulated in studies of semantic processing. As already discussed, the N400 is sensitive to many stimulus-related variables that have notable effects on reaction times: repetition, word frequency, orthographic neighborhood density, semantic priming, and contextual plausibility, just to name a few. Strikingly, however, these variables affect the amplitude of the N400 *but not its latency*. Task-related variables that affect, for example, the availability of attentional resources, the depth with which stimuli are processed, or the difficulty of stimulus selection or stimulus-to-response mapping also affect only the amplitude of the N400 (when they have effects at all).

The temporal stability of the N400 contrasts not only with behavioral patterns, where similar types of manipulations to those conducted in ERP studies do result in response time differences, but also with effects seen on other electrophysiological components linked to stimulus processing and evaluation. P300 responses (recall that the P300 was the ERP that component Kutas and Hillyard, 1980b, initially expected to see in response to semantic anomalies) do shift in latency in response to stimulus and task related variables that make stimulus evaluation more difficult (e.g., Kutas & Donchin, 1976; Kutas, McCarthy, & Donchin, 1977; McCarthy & Donchin, 1981). For example, Kutas, McCarthy, and Donchin (1977) asked participants to classify verbal stimuli at three different levels of difficulty detecting infrequent presentations of the name "Nancy" among frequent presentations of the name "David," detecting infrequent presentations of any female name among frequent presentations of male names, and detecting synonyms of a particular word among frequent presentations of a wide variety of words that were not synonyms. When accuracy was emphasized, P300 latencies increased systematically with the difficulty of the classification (latest for synonyms and earliest for Nancy-among-David), as did response times. Interestingly, when speed was instead emphasized, P300 latencies again tracked with task difficulty, but reaction times were no longer strongly correlated with those latencies. This pattern, along with that seen in other studies, strongly suggests that P300 latency reflects stimulus evaluation difficulty, independent of factors that influence the speed with which a response is selected or executed (although see Verleger, 1997 for a different view). Indeed, under speeded conditions, responses sometimes precede the peak of the P300, suggesting that participants occasionally respond before stimuli are fully evaluated.

The behavioral and P300 data strongly suggest that the time needed to process and evaluate stimuli varies depending on the nature of those stimuli and the context and task environment in which they occur, an idea that seems both intuitive and noncontentious. It is thus especially striking that N400 latencies do not shift to accommodate task difficulty or context. A reasonable (and tantalizing) hypothesis, then, is that the latency of the N400 does not vary because its temporal stability serves a functionally critical purpose. We posit that this purpose may be to bind—through temporal coherence—diverse, spatially distributed information into a coincidentally active neurophsyiological unit that is experienced as the meaning of the eliciting stimulus. This type of temporal binding process is a core component of Pulvermuller's (1999) Hebbian cell-assembly view of semantics, and similar proposals have been put forward in the context of object perception (Hummel & Biederman, 1992; Singer & Gray, 1995; Treisman, 1996; von der Malsburg, 1995), attention and consciousness (Engel & Singer, 2001; Niebur, Koch, & Rosin, 1993), recall (Damasio, 1989), response selection (Roelfsema, Engel, Kœnig, & Singer, 1996), and higher level reasoning (Hummel & Holyoak, 2005; Shastri & Ajjanagadde, 1993). The N400 may be the scalp manifestation of this temporally synchronous activity, which should be relatively obligatorily elicited by sensory stimuli in all modalities and bear a similar, predictable temporal relationship to those stimuli—as the N400 does. Indeed, the medial temporal lobe, which, as discussed, seems to be a critical source of N400 activity, is well positioned to mediate such temporal binding. It seems to be a shared pinnacle of the input stream for visual, auditory, somatosensory, and olfactory information and contains connections to other multimodal processing areas such as the frontal lobes and hippocampus (e.g., Brown & Bashir, 2002).

5.1. How When Determines What

The fact that the electrical activity underlying the N400 occurs with a fixed temporal relationship to an eliciting stimulus has some important, and perhaps surprising, consequences for our understanding of semantic processing. First, it suggests that the nature of the initial meaning representation of a given stimulus is critically dependent on what information is able to come online before the binding process is initiated. Indeed, the field has long noted that there are semantically relevant variables that do not seem to influence N400 amplitudes. As mentioned briefly already, N400 amplitudes are sensitive to hierarchical category relationships, as can be seen in sentence verification paradigms. However, in these paradigms, N400 amplitude often does not track the truth value of the sentence, patterning instead with the association between the subject and predicate. That is, responses are identical to "A robin is/is not a tree" (with large amplitude N400s seen to both) and to "A robin is/is not a bird" (with smaller amplitude N400s seen to both). This result, originally reported by Fischler et al. (1983) has been extended to other qualifiers (e.g., all, no, some; Kounios & Holcomb, 1992) and to information gleaned from pictures immediately following verbal prime sentence ("in front of the tower there is a/no ghost"; Ludtke, Friedrich, De Filippis, & Kaup, 2008). This pattern is consistent with behavioral data and models arising from that data that suggest that negation often has a relatively late effect on comprehension (e.g., Kaup, Ludtke, & Zwaan, 2006). If information about negation (and other type of qualification) becomes available late in comprehension, it cannot influence the representation that is formed at the temporally fixed point of the N400 binding process. The fact that it is timing, and not some inherent property of the negation process, that constrains its influence on the N400 is supported by data showing that negation does affect the N400 in the sentence–picture verification paradigm when there is a long delay between the sentence prime containing the negation and the onset of the picture (Ludtke et al., 2008).

Thematic role assignment is another type of information that has, perhaps surprisingly, been found not to impact N400 amplitudes (Hoeks, Stowe, & Doedens, 2004; Kuperberg, Kreher, Sitnikova, Caplan, & Holcomb, 2007; Kuperberg, Sitnikova, Caplan, & Holcomb, 2003). For example, Kuperberg et al. (2003) presented participants with sentences that included a pragmatic violation, a thematic role violation, or no violation, as in:

- Pragmatic violation: For breakfast the boys would only bury . . .
- Thematic violation: For breakfast the eggs would only eat . . .
- No violation: For breakfast the boys would only eat . . .

N400 amplitudes were larger for the pragmatic violation (''For breakfast the boys would only *bury*'') than for the item with no violation, replicating many similar findings in the literature. However, N400 amplitudes were of similar size for the thematic violation (''For breakfast the eggs would only *eat*'') and the no violation item (''For breakfast the boys would only *eat*''), despite the fact that the eggs rarely eat breakfast, meaning that the thematic violation item is clearly less plausible than the no violation item. The fact that pragmatic violations do elicit larger N400s than thematic violations or well-formed items suggests that pragmatic information becomes available by the time of N400 processing. Most theories would assume that a phrase structure has also already been created for the sentence by this point. However, it would seem that the time required to map the semantics of particular words onto the syntactic phrase structure information in order to determine each word's thematic role exceeds the point at which the N400 is triggered. In other words, at the time of the N400, the system does not yet seem to be aware that in the thematic violation above, the word eggs is being infelicitously bound to the subject role of the eating event (as opposed to, e.g., the more plausible object role.)

Although some kinds of information (such as thematic role) may rarely (if ever) be available to influence N400 processing and other kinds of information (such as orthographic neighborhood size) may almost always be available, there are classes of information whose availability is likely to be more variable across people and circumstances. For example, there is a growing body of data showing that the brain actively uses context information to predict—that is, to anticipate and prepare to process—features of likely upcoming stimuli (DeLong, Urbach, & Kutas, 2005; Federmeier & Kutas, 1999; Federmeier, McLennan, De Ochoa, & Kutas, 2002; Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005; Wicha et al., 2003; see review by Federmeier, 2007). As already described, N400 responses are reduced to "baseball" as compared with "chess" in the context of "He caught the pass and scored another touchdown. There was nothing he enjoyed more than a good game of . . . ." This facilitation seems to arise because of the semantic overlap between "baseball" and the expected—but never actually presented—word "football." Indeed, the amount of facilitation for words like "baseball" increases proportionally to the level of constraint (and thus prediction for) the corresponding expected words (Federmeier & Kutas, 1999; Federmeier et al., 2007; see also DeLong et al., 2005).

However, as can be seen in Figure 6, N400 responses to these same sentences in older adults do not show the prediction-related pattern (Federmeier et al., 2002). This change is consistent with more general findings suggesting that older adults become slower and less effective at making use of message-level context information during sentence processing (e.g., Federmeier & Kutas, 2005; Federmeier, van Petten, Schwartz, & Kutas, 2003). If older adults process context information more slowly, then prediction-related information may simply not become available in time to

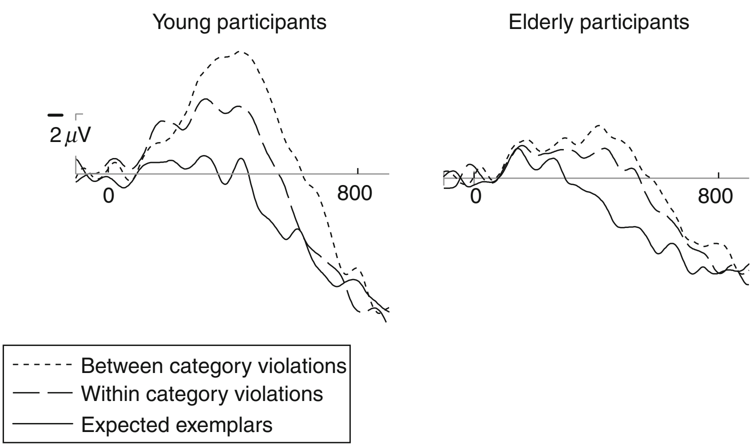

Figure 6 Aging effects on predictive processing, as indexed by the N400. Young adults (at left) show N400 facilitation for incongruent sentence-final words that are categorically related to an expected (but never presented) completion. For example, N400 responses are smaller to "baseball" (a "within category violation") than to "chess" (a "between category violation") in the sentence context: "He caught the pass and scored another touchdown. There was nothing he enjoyed more than a good game of. . ." (where "football" is the "expected exemplar"). This pattern points to the use of predictive processing mechanisms during comprehension, which preactivate features of likely upcoming words—thereby affording a processing benefit to other words that share those features. However, as a group, healthy older adults (at right) fail to show this pattern, suggesting that the use of predictive processing during comprehension becomes less likely or less effective with age.

influence the N400. Consistent with this suggestion, older adults with higher verbal fluency—that is, who can generate more words that fit a particular category in a set amount of time—actually do show prediction-related effects on the N400, similar to younger participants (Federmeier et al., 2002). Thus, quantitative shifts in the timing of processing can potentially lead to qualitative differences in what particular facets of semantics come to be linked up with a given input.

5.2. Semantics Beyond the N400

The fact that time, rather than task, seems to constrain the semantic information that is initially accessed in response to a given input and, moreover, that some critical information may not be available within those time constraints strongly suggests that semantic processing should not be conceived of as a single, discrete processing stage. Instead, effects related to meaning processing would be expected to occur after the N400 time window as the language comprehension system adds to, subtracts from, or otherwise modifies the activation that was established in the initial "sweep" of semantic memory during the N400.

In line with this suggestion, a number of post-N400 semantic effects have been documented. One is a posterior positivity that follows the N400 (seen between about 500 and 800 ms poststimulus onset; see review by Kutas, Federmeier, Staab, & Kluender, 2007) that is sometimes referred to as a P600 and linked to language (especially syntactic) revision processes and sometimes referred to as the Late Positive Complex (LPC) and linked to explicit aspects of memory retrieval; whether the "P600" and the "LPC" are in fact the same or related effects or whether there are multiple functionally and neurally different positivities that follow the N400 is beyond the scope of this discussion. The critical observation to be made about such late language components is that they often show effects of semantic variables that fail to influence N400 amplitudes. For example, although the thematic role violations (eggs eating breakfast) described in Section 5.1 are not associated with larger N400 responses, they do elicit enhanced posterior positivities (Hoeks et al., 2004; Kuperberg et al., 2003, 2007). In the example discussed earlier, the lexical association between "eggs" and "breakfast" that was facilitated on the N400 was later recognized by the comprehension system to contain an error with import for meaning, resulting in the elicitation of a late positivity. In other cases, information which fails to facilitate N400 responses has its effects on a post-N400 positivity. For example, the semantically ambiguous word "organ" will normally prime a word associated with one of its meanings (e.g., "kidney," "piano"), resulting in reduced N400 amplitudes. However, when prior context information biases one meaning of the homograph (e.g., the word "piano" precedes the word "organ"), N400 responses to a subsequent target related to the other meaning are not facilitated as compared with an unrelated baseline condition (Meyer & Federmeier, 2007). Enhanced posterior positivity is, however, observed to these subsequent target items suggesting that the previously suppressed meaning eventually does become available—just not in time to affect N400 processing.

Other post-N400 ERP responses related to semantic processing include a frontal negativity that has been observed in association with active meaning selection processes engendered by ambiguity (e.g., Federmeier, Segal, Lombrozo, & Kutas, 2000; Lee & Federmeier, 2006). Interestingly, this frontal negativity is not observed when context provides disambiguating information sufficiently in advance of the ambiguous input (Lee & Federmeier, 2009; Van Petten & Kutas, 1987), in which case effects on the N400 are sometimes observed instead (Lee & Federmeier, 2009). A frontally distributed positivity has also been observed and linked to processes involved in meaning revision (Federmeier, Wlotko, De Ochoa-Dewald, & Kutas, 2007). Another aspect of the N400's specificity to activity elicited in temporal synchrony with a particular input is its general insensitivity to contextual constraint (e.g., Kutas & Hillyard, 1984). Some contexts (e.g., "He bought her a pearl necklace for her . . . ") lead to fairly strong expectations for particular upcoming words ("birthday"), whereas other contexts (e.g., "He looked worried because he might have broken his . . .") lead to much weaker and more varied expectations ("arm"?). Thus, the state of the semantic system would seem to be different following the presentation of these two context types. However, N400 responses to unexpected but plausible words (e.g., "collection" in either context above) are identical in the two constraint conditions. Thus, although N400 amplitudes clearly track whether the context has preactivated meaning features associated with a given input, they do not seem to track the activation state of other, unassociated meaning features. Unexpected items in strongly constraining contexts, however, elicit enhanced frontal positivity that would seem to be related to the need to suppress or revise the contextually induced expectation for a different word (Federmeier et al., 2007).

These effects, and others like them, make clear that the meaning of a given input and of the higher level context in which it occurs emerges over time as the result of multiple kinds of processes (with multiple neural roots). Some of these processes, like the N400, seem to be ubiquitous and automatic but critically constrained by the timecourse with which different kinds of information become available in different contexts and in different people. Other processes, which appear to be recruited in a more strategic and possibly more flexible manner as new information becomes available, then serve to update or repair the initial meaning representation and to link it in to higher level meaning structures. These processes may be subject to less stringent temporal constraints than the N400, although at least some models suggest that timing and temporal synchrony play a critical role in these higher order meaning analyses as well (e.g., Hummel & Holyoak, 2003).

6. Conclusions

The ease with which meaning is experienced belies the critical challenge that constructing that meaning poses to the brain. Although there is not yet a "Dewey Decimal System" of the human brain, studies of patients and work using brain imaging techniques with good spatial resolution have revealed that meaning resides in a complex, spatially distributed neural network. Information must be rapidly accessed from this network, in a manner that is stable and stimulus-driven yet also flexible and context-dependent. And, somehow, these distributed activation states must be reliably linked up with one another, and with the eliciting stimulus, to yield stable, conceptual-level representations. Determining how this comes to be accomplished is arguably one of the central challenges for the development of a neurally and cognitively plausible model of human cognition.

In this chapter we have argued that a central component of any such model will have to be time. Electrophysiological data reveal that activity in a spatially distributed brain network converges around 400 ms after stimulus onset and can be measured at the scalp as a widely distributed negative-going voltage deflection. This N400 activity is elicited by meaningful stimuli of all types in all modalities, in a manner that is sensitive to attention but that does not seem to require attention. Temporal lobe activity seems to be an important source for this scalp-recorded component, although the distribution of the N400 response varies with stimulus type and modality, suggesting that somewhat different configurations of meaning-related information come online in response to different types of inputs. The amplitude of the N400 is sensitive to the full range of variables that would be expected to affect the ease with which an initial semantic representation can be built, including factors such as repetition and frequency and context information of all types and levels. Its latency, however, is remarkably invariant, suggesting that time, and timing, serves as an essential binding force. Time not only seems to bind meaning-related information together, but also to constrain the binding process itself. Information that is not available by the time the temporally constrained binding process is elicited must be incorporated later, as additional processes come online to modify the initial semantic representation. In other words, there is a "time for meaning," and the fact that semantic information must be *on* time necessitates that the full appreciation of meaning happen *through* time.

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CHAPTER TWO

Design for a Working Memory

Klaus Oberauer

Contents

Abstract

Starting from the premise that working memory is a system for providing access to representations for complex cognition, six requirements for a working memory system are delineated: (1) maintaining structural representations by dynamic bindings, (2) manipulating structural representations, (3) flexible reconfiguration, (4) partial decoupling from long-term memory, (5) controlled retrieval from long-term memory, and (6) encoding of new structures into long-term memory. The chapter proposes an architecture for a system that meets these requirements. The working memory system consists of a declarative and a procedural part, each of which has three embedded components: the activated part of long-term memory, a component for creating new structural representations by dynamic bindings (the "region of direct access" for declarative working memory, and the "bridge" for procedural working memory), and a

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mechanism for selecting a single element ("focus of attention" for declarative working memory, and "response focus" for procedural working memory). The architecture affords two modes of information processing, an analytical and an associative mode. This distinction provides a theoretically founded formulation of a dual-process theory of reasoning.

1. Six Requirements for a Working Memory System

The study of working memory (WM) has its roots in the investigation of immediate recall of short lists of items such as a telephone number or a list of unconnected words (Blankenship, 1938; Nipher, 1878). Until today most research on WM is devoted to what has become known as *memory span* tasks. The seventies of the last century have witnessed an extension of the scope of the concept of WM, now defined as a device for simultaneous storage and processing (Baddeley & Hitch, 1974), and with it came the introduction of so-called *complex span* tasks that combine the immediate recall of lists with a concurrent processing task such as reading (Daneman & Carpenter, 1980). The construct such developed has become a big success not least because complex span tasks have turned out to be strong predictors of performance in complex cognitive activities such as text comprehension and reasoning (Daneman & Merikle, 1996; Kyllonen & Christal, 1990; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002), and are strongly related even to general intelligence (Conway, Kane, & Engle, 2003).

As theorists have recognized for some time now (e.g., Baddeley, 1986; Just & Carpenter, 1992), WM has certainly not evolved to help us remember telephone numbers (whether on their own or while reading unrelated sentences). This insight nourishes the suspicion that the tasks commonly used to operationalize WM are more a reflection of the historical development of the field than of our theoretical understanding of its object. I think this is unfortunate because much research is devoted to understanding the particular tasks that happen to have emerged as established operationalizations of WM, asking questions such as "What happens in the reading span task?" instead of, "How does working memory work?"

In this chapter, I want to pursue a functional approach to WM. I will start from an assumption about what WM is good for and attempt to delineate some minimal requirements of a system that serves this function. This approach is akin to Marr's (1982) strategy to understand vision through a computational analysis of what the visual system must accomplish, although my analysis will not yet reach the degree of formal precision that he achieved. The leading idea is that form follows function, so that an analysis of the function a system is to accomplish provides useful constraints for its architecture and its mechanisms.

I assume that WM is a system devoted to providing access to representations for goal-directed processing. At least in humans this involves processes such as language comprehension, reasoning, planning, hypothetical thinking, and creative problem solving. Success in all these activities, which I will refer to as complex cognition, is highly correlated with measures of WM capacity (for a review see Oberauer, Süß, Wilhelm, & Sander, 2007). One common characteristic of all varieties of complex cognition is that they require the flexible combination of representations into new structures (Halford, Wilson, & Phillips, 1998; Oberauer et al., 2007), and the goal-directed manipulation of these structures.

I propose that a system serving complex cognition must meet at least the following six demands: First, it must be able to build and maintain new structural representations. For instance, the system must represent new propositions, new sequences of actions in a plan, or new constellations of pieces on a chessboard. Building new structural representations requires a mechanism for *dynamic binding*, that is, for binding content elements such as words, objects, or events, to places in a cognitive coordinate system or to variables in a schema. For instance, objects must be bound to locations in physical space, events to locations on the temporal dimension, and words to variables in syntactical and propositional schemata. These bindings must be dynamic, which means that they can be set up quickly and dissolved quickly when the structure is updated or discarded.

Second, complex cognition involves manipulating structural representations. This means that there must be a mechanism for selectively accessing one or a few elements within a structure and submitting them to a cognitive operation. For instance, mentally simulating a chess move involves picking out one figure and moving it across the board, while all other figures stay in their positions. This requirement calls for an *attentional selection* mechanism for contents of WM. In addition, the system must have a mechanism for deciding what to do with the selected element. This requirement points to the need for a *procedural* system that represents condition-action rules (e.g., procedures for deciding which moves to consider in a mental simulation, given a constellation on the chessboard, and procedures for moving the figures).

Third, WM is a general-purpose mechanism, not a module designed for solving a particular problem. Therefore, it must be possible to flexibly reconfigure it. This requirement points to the need for *executive processes*, that is, processes that control its operations and configures its parameters according to representations of goals. For instance, WM would operate differently when the goal is to remember a constellation of pieces on a chessboard than when the goal is to play a game, and it would operate differently in speed chess than in ordinary chess.

The fourth requirement follows from the need for rapid updating of structural representations and of the procedures acting on them:

Representations in WM must be partially decoupled from knowledge and episodic memories in *long-term memory* (LTM). A chess player mentally simulating two or three moves must be able to distinguish the representation of a hypothetical board constellation from the many representations of similar constellations that he remembers from previous games. He must also be able to distinguish the constellation that follows after an imagined move from the constellation before that move. In general, manipulation of structural representations means that the structure is frequently updated, and therefore, WM must be able to avoid proactive interference from the previously held representations on the current one. Likewise, the flexible implementation of different goals requires frequent updating of procedural representations, and therefore, WM must also be able to avoid proactive interference from habits and routines.

Fifth, WM needs to be able to draw on relevant contents of LTM. This implies that LTM representations that could be helpful for the problem at hand can be retrieved efficiently. This need creates an obvious tension with the requirement for decoupling WM representations from LTM. Thus, the system must decide on when to allow LTM to influence the contents of WM and when to block them off.

Finally, working out the solution to a problem would lose much of its worth if the solution would be quickly forgotten once the system is engaged with something else. Therefore, new structural representations built in WM must be transferred into LTM. This means that there must be a mechanism for transforming temporary, dynamic bindings into more permanent structural representations.

In this chapter, I will propose a blueprint for a system that meets these requirements. Section 2 will sketch the architecture of WM, delineating mechanisms for meeting the first three requirements. Section 3 will discuss the interaction between WM and LTM, offering some speculations on how the system meets the remaining three requirements. The structure of the chapter does not follow strictly the list of the six requirements; therefore, Table 1 makes explicit which component of the WM system address which requirement and provides pointers to the sections explaining these components.

2. The Architecture of Working Memory

I will propose a sketch of the architecture of WM that is suited to fulfill the functions introduced above. The core of the framework has first been developed to accommodate empirical evidence (Cowan, 1988; Oberauer, 2002); here I will flesh it out by giving it a functional interpretation, and by adding further assumptions and components, hoping that the elaborated framework will prove useful as a blueprint for a system that serves complex cognition.

Table 1 The Six Requirements for a Working Memory System, the Components Assumed to Be Responsible for Them, and Where They Are Addressed in the Text.

Requirement	Component	Sections
1. Structural representations	Region of direct access	2.1.2
	Bridge	2.2
2. Manipulation	Focus of attention	2.1.3
	Procedural WM	2.2
3. Flexible reconfiguration	Executive processes	2.2.2
4. Partial decoupling from LTM	Distinction between activated LTM and central components	2.1
	Control of retrieval from LTM	3.3
5. Retrieval from LTM	Retrieval and unpacking of chunks	3.2.2
6. Encoding of structural information into LTM	Chunking of structural information	3.2.1

A first and fundamental design decision is to distinguish between declarative and procedural WM. The declarative part is responsible for making representations available for processing, whereas the procedural part is responsible for doing the processing. In a sense, the declarative system is the memory part, and the procedural system is the working part of working memory. The distinction between declarative and procedural memory lies at the heart of production system architectures such as ACT (Anderson, 1983), SOAR (Newell, 1990), and ACT-R (Anderson & Lebiere, 1998), but its implications for WM have not been spelled out (for one previous reference to "procedural working memory" see Monsell, 2003). In much of the WM literature its place has been taken by the distinction between the *central executive* and the *slave systems* (Baddeley, 1986). In my view this is an unfortunate conceptualization because the procedural part of the system is no more central than the declarative part. Others have treated the terms *working memory* and *executive system* as largely equivalent, or the former as a subset of the latter. This is even more unfortunate because it blurs the important distinction between the declarative and the procedural aspects. Moreover, not every process executed can be regarded as an executive process without draining the concept *executive* of all useful meaning. Here I will make a distinction between the primary processes carrying out the manipulations required for a task, such as mentally moving a pawn on a chessboard, or deciding whether to press the left or the right button in a speeded choice task, and executive processes that supervise and control the primary processes, such as the decision to switch to another task, to update the current WM contents by new information, or to sacrifice accuracy for speed in a choice task.

2.1. Declarative Working Memory

The declarative part of WM, illustrated in Figure 1, consists of three components that constitute three embedded sets of representations, the activated part of LTM, the region of direct access (DA region), and the focus of attention. Functionally, the three components can be seen as three levels of selection of representations, with each component narrowing down the selected set more than the preceding one. In addition, the three components have qualitatively distinct functions for the construction and manipulation of representations, as I will elaborate below.

2.1.1. Activated Long-Term Memory

I conceptualize LTM as an associative network of representations that activate each other automatically along their associations. The advantage of such a system is that it is content addressable: Given any piece of information, related information can quickly be activated, such that a

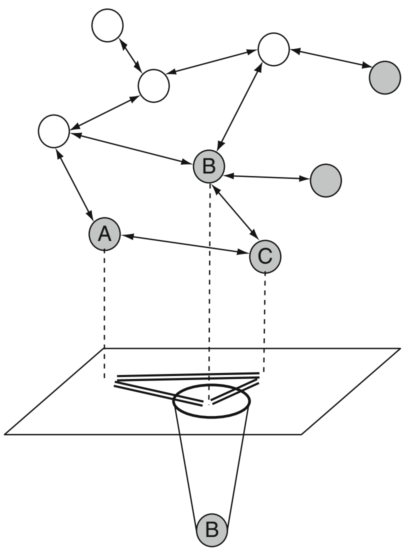

Figure 1 *Architecture of declarative working memory*. Small circles represent elements of declarative representations in long-term memory. Shaded units are activated above baseline. A subset of three elements (labeled A, B, and C) are bound to positions in a mental space, depicted here as the rectangular frame. This subset of elements constitutes the content of the region of direct access. Thin continuous arrows are associations in LTM; dotted lines are temporary bindings; double lines are relations between elements in the region of direct access that emerge from their relative positions in the mental space. One of the positions in mental space is selected by the focus of attention (large thick-lined oval); the element bound to that position (B) is thereby selected for processing.

whole set of tightly interconnected representations can be recreated from any subset as cue. This idea is incorporated in virtually all current theories and models of LTM (e.g., Anderson & Lebiere, 1998; Gillund & Shiffrin, 1984; McClelland, McNaughton, & O'Reilly, 1995).

An assumption that is not shared by all models is that, in LTM, there is no strict separation between declarative and procedural knowledge. Rather, declarative representations are associated with procedures, such that the activation of a declarative representation such as an object, an event, a situation, or a fact automatically activates an associated cognitive operation (e.g., drawing an inference based on an activated stereotype), evaluation (e.g., assessing an event as positive), or physical action (e.g., performing a left-directed action in response to a stimulus on the left side). These associations enable information processing that bypasses the more central components of WM. I will return to the power and the limitations of associative information processing in Section 4.

Representations in LTM are activated by perceptual input or through spread of activation from other, associated representations, including representations of goals. The currently activated subset of representations forms the activated part of LTM. The degree of activation of a representation is an implicit code of its expected relevance for the current situation and the current goal (Anderson & Lebiere, 1998), and its function is to make more relevant representations more available for processing.

The increased availability of activated representations is reflected in three consequences of activation. First, perceptual stimuli corresponding to already activated representations in LTM are processed more efficiently and can thereby be identified (i.e., categorized) faster and with higher accuracy. Thus, activation contributes to priming. This gain in perceptual fluency generates a signal of familiarity of the stimulus that can be used, among other things, to inform recognition decisions (Whittlesea, Jacoby, & Girard, 1990).[1]

Second, a representation is more likely to be retrieved, and its retrieval takes less time, the higher its activation (for a formal development of these assumptions see Anderson & Lebiere, 1998). Retrieval means to project a representation into the more central component, the region of direct access, where it can be manipulated and combined with other representations. The third consequence is that activated declarative representations, through their associations to procedural representations, generate tendencies for or against associated inferences and decisions, a point to which I will return Section 4.

[1] It should be added that both repetition priming and familiarity cannot be attributed only to temporary activation of representations, because both can last for times much longer than activation can plausibly be assumed to continue—in one instance, up to 17 years (Mitchell, 2006). I assume that activation in LTM drives familiarity only in short-term recognition paradigms in which the recognition decision follows initial presentation within a few seconds.

2.1.2. The Direct-Access Region

The main function of the DA region is to render a small number of distinct elements immediately accessible, and to integrate them into a structure. There are two ways of building new structures, both of which involve binding of content representations to context representations. One is to draw on existing structure templates or schemata, such as the schema for a proposition, which has an action at its core and relates it to arguments such as the role of an agent ("who does it?"), an object ("to who or what is it done?"), and other, optional roles such as instrument ("with what was it done?") or time ("when did it happen?"). The template arguments are variables to which elements from large classes of concepts can be bound, enabling us to build a virtually infinite variety of structures. For instance, we can make sense of linguistic input such as: "The parrot beats the sheep with a cucumber" by binding the concept of *beating* to the action variable, the concept of *parrot* to the agent variable, and so on.

Another way to build structures is by binding each element to a position in a common cognitive coordinate system. A cognitive coordinate system is a mental space that can be used to literally represent physical space, or to metaphorically represent other continuous dimensions such as time or some quantitative variable (e.g., size, brightness, pitch, intelligence, etc.). For example, I could represent my knowledge that the population of China is larger than that of India by placing a token or symbol for China on top of one for India in my mental space. I could then proceed to add the knowledge that the population of India is larger than that of Russia by placing a representation of Russia below that of India. By being placed in a common coordinate system every element is related to every other, and this can bring out new relations that were not explicitly represented before, for instance, the relation between the population sizes of China and Russia. This relation is constrained by the spatial nature of the coordinate system that, in this case, enforces that Russia is placed below China, so that I can infer that the population of Russia must be smaller than that of China even if I never thought about this relation before. This is, in a nutshell, the mechanism of deductive reasoning as described by the theory of mental models (Goodwin & Johnson-Laird, 2005; Johnson-Laird & Byrne, 1991).

Binding elements into a multidimensional cognitive coordinate system is also indispensable for inductive reasoning. The core operation of inductive reasoning is to compare two entities to identify similarities and differences between them. To go beyond global judgments of similarity, the reasoner must approach the task in an analytic way, that is, distinguish relevant features of the two entities and make separate comparisons with regard to each feature. For instance, a person can judge that an orange and a tennis ball are similar with regard to size and color, but differ with regard to edibility. These relations can be represented simultaneously by placing the two objects into a three-dimensional coordinate system in which the three dimensions are assigned to the three feature dimensions selected for comparison. Simultaneous representation of similarities and differences on several feature dimensions is a key in many inductive-reasoning tasks that feature in intelligence tests, such as the Raven matrices (Klauer, 1996).

The examples discussed above illustrate that the DA region recruits a spatial medium of representation as a projection screen for relations on nonspatial dimensions, by assigning to its dimensions, for instance, physical space, time, and any feature dimension on which entities could be compared. The prevalence of spatial metaphors for nonspatial relations has been noted in studies reaching from semantics (Lakoff & Johnson, 1980) to logical reasoning (DeSoto, London, & Handel, 1965; Knauff, Mulack, Kassubek, Salih, & Greenlee, 2002) to social psychology (Bar-Anan, Liberman, Trope, & Algom, 2007). I believe this prevalence reflects the fact that space is used as a generic medium for building structural representations in the region of direct access.

To summarize, the region of direct access is a mechanism for establishing and holding temporary bindings between contents (e.g., objects, events, words) and contexts (i.e., argument variables in structure templates, or positions in a generic cognitive coordinate system). By supporting arbitrary bindings between virtually any content with any context, this system enables the compositionality of thought that many theorists regard as a hallmark of human cognition (Fodor & Pylyshyn, 1988): We can create an unlimited number of different ideas by freely combining content elements into new structures.

I assume that the DA region has a limited capacity that limits the complexity of structural representations that can be assembled by temporary bindings. The common variance reflected by measures of WM capacity (reviewed in Oberauer, 2005c) reflects essentially this capacity limit. The capacity limit arises from two sources, *retrieval competition* and *representational interference*. First, with an increasing number of context-to-content bindings, the attempt to retrieve one particular content element, cued by its context, suffers more competition from other contents bound to related contexts. The increasing degree of retrieval competition, however, cannot alone explain the steep decline of performance as the load on the DA region increases (Oberauer & Kliegl, 2001). Therefore, I assume a second form of interference by which the content representations bound in the DA region mutually degrade each other. Various candidate mechanisms for representational interference are currently explored through computational modeling, among them the superposition of content–context bindings in a common weight matrix (Farrell & Lewandowsky, 2002; Oberauer & Lewandowsky, 2008), and the overwriting of features shared by different contents in the DA region (Nairne, 1990; Oberauer & Kliegl, 2006; Oberauer & Lange, 2008).

2.1.3. The Focus of Attention

Reasoning not only involves the creation of structural representations but also their manipulation. For instance, we could use the array of three countries described above to play through what would happen if the population of China declined. We simply move the China token down along the dimension that represents population size while holding the other two elements in place—this might bring us to the conclusion that eventually the relative order of China and India will reverse while that of China with Russia stays the same. Selecting the target of a manipulation is the function of the focus of attention. It picks out one element among those currently held in the DA region and uses it as the object of a cognitive operation, in this case the operation of simulating a population decrease. My use of the concept of *attention* as applied to the contents of WM is based on an understanding of attention in purely functional terms, referring to a mechanism for the selection of representations for (cognitive) action (Allport, 1987).

This discussion of the focus of attention points back to a second function of the DA region. The contents of the DA region figure as the *selection set* for the focus of attention, that is, a small set of elements that are candidates for being brought into the focus. The focus of attention has direct access to these elements either through their content (e.g., when instructed to "move India up") or through their bindings to their places in the coordinate system (e.g., when asked "which one is highest?"). Access to contents through their current contexts is what I mean by "direct access." The role in a template, or place in a coordinate system, serves as a temporary address to which any arbitrary representation can be bound so that it can be accessed without any knowledge about its content.

2.1.4. Evidence for the Three Components of Declarative Working Memory

Consider the following task: You are asked to encode two short lists of digits for a short-term memory test, presented in two rows of boxes on a computer screen. After the digits are erased, one list is declared as temporarily irrelevant for the task. Next, you must perform a series of arithmetic operations on selected digits of the remaining list. The operations (e.g., "+2" or "−4") are displayed in one of the boxes of the relevant list, and you should retrieve the digit initially presented in that box, apply the arithmetic operation to it, and type the response as quickly as possible. This response is immediately followed by the next operation displayed in the same or a different box of the relevant list (see Figure 2). At the end of a series of operations, you are asked to recall both lists.

This paradigm (Oberauer, 2002) places clearly definable demands on all three components of declarative WM, and provides evidence for their

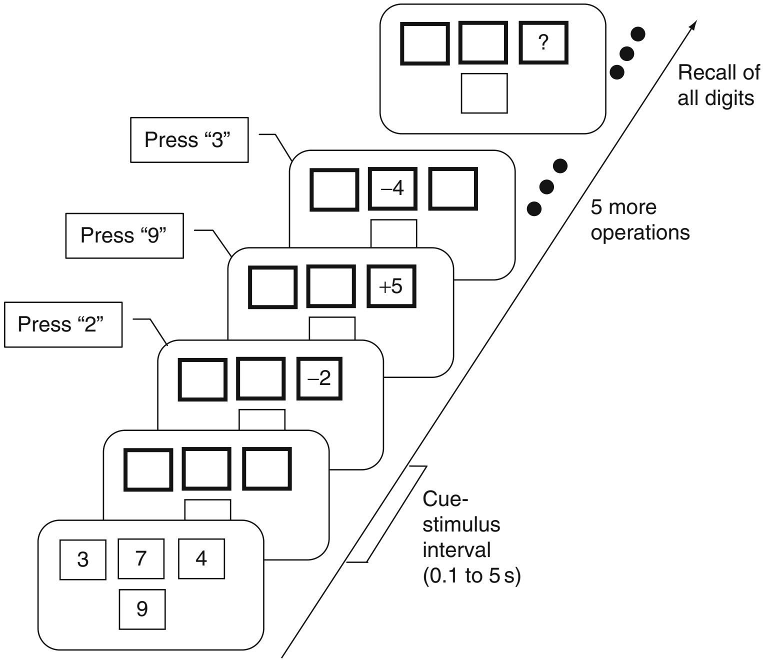

Figure 2 Sequence of events in a trial of Experiment 2 in Oberauer (2002). The trial has a relevant-set size of three and an irrelevant-set size of 1; the relevant set is cued by its frames turning red (illustrated here by thick lines). The third operation involves an object switch; the second is an object repetition.

distinction (for an illustration of how declarative WM applies to that paradigm, see Figure 3). Initially, all digits must be linked to their boxes by temporary bindings. These bindings make the digits directly accessible through their places in the cognitive coordinate system, that is, the boxes. Binding the digits to neighboring places in this episodic context integrates them into a structure in the DA region. The contexts of individual digits are not perfectly distinct, and therefore, cueing one of them—by placing an arithmetic operation in one box—also partially cues all other digits in the DA region, such that they all compete to some degree for being selected into the focus of attention. This competition leads to an increase of retrieval latencies with the set size of digits held in the DA region. This set-size effect is further compounded by representational interference (Oberauer & Kliegl, 2006). The results from my experiment were in line with these assumptions: When the first arithmetic operation was required immediately after the cue that designates the relevant list, response times to that operation increased with the length (or set size) of both lists (Oberauer, 2002).

Once people know which list will be used for the arithmetic operations, they can afford removing the other, temporarily irrelevant list from the DA

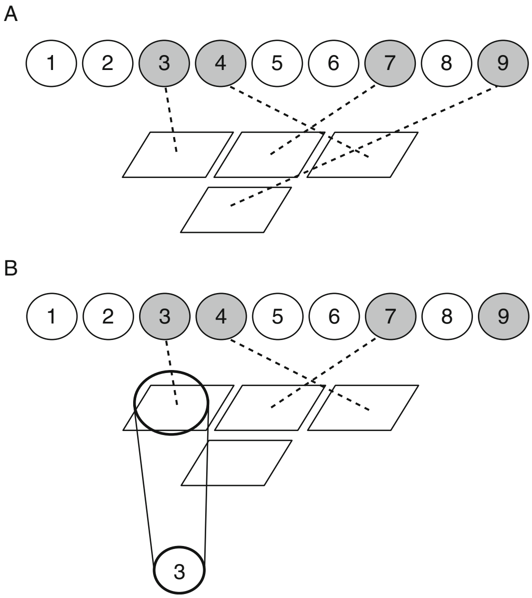

Figure 3 Declarative working memory operating on a trial of Experiment 2 in Oberauer (2002). Panel (A) illustrates the state immediately after encoding both lists. The small circles on top are representations of digits in LTM; those included in the present lists are activated (illustrated by shading). Digits are bound to their positions on the screen (thick dotted lines). Panel (B) reflects the state after the irrelevant list has been removed from the direct-access region—its bindings have been cut, but its content, the single digit 9, remains activated in LTM. The left-most digit of the relevant list must be accessed for processing, and the focus of attention (thick-lined oval) selects that location and uses it as a cue to retrieve the digit bound to it.

region, because they do not need to access its elements for the arithmetic task. Because that list will have to be recalled at the end of the trial, however, it must first be encoded into the activated part of LTM. This process takes about 2 s: Over the first 2 s after the cue that designates the relevant list, the set-size effect of the irrelevant list gradually drops to zero, while the set-size effect of the relevant list remains unchanged (Oberauer, 2002).

The WM system seems to have remarkable flexibility in swapping contents between the DA region and activated LTM. A list of digits or words that is not needed for processing only temporarily is still removed from the DA region within about 2 s, as reflected in the elimination of set-size effects. When that list is later cued as relevant for processing, it is brought back into the DA region—and the set-size effect on reaction times reappears (Oberauer, 2005b). With this list-switching procedure we can also measure the time it takes to switch between two list, that is, remove one from the DA region and replace it by another by retrieving it from activated LTM. In two experiments, I found these *list-switching costs* to depend on the set size of the to-be-removed list, but not on the set size of the to-be-retrieved list (Oberauer, 2005b). The lack of a set-size effect for the list retrieved into the DA region suggests that this list is retrieved as a single chunk from activated LTM, an assumption to which I will return in the section on the interaction of WM with LTM.

Evidence for the focus of attention within the DA region comes from a further finding: When an arithmetic operation must be applied to the same digit as in the preceding step, latencies are shorter than when a different digit in the relevant set must be accessed. These so-called *object-switch costs* (Garavan, 1998; Oberauer, 2003) can be interpreted as the time it takes for the focus of attention to select a new element from the set held in the DA region. Supporting this interpretation, the object-switch costs increase with the length of the relevant list (Oberauer, 2003) but not with the length of the irrelevant list (Oberauer, 2002).

Object-switch costs are found in tasks in which an item from the memory set must be retrieved and used in a cognitive operation, and also in tasks in which the item is updated by replacing it with a new item (Oberauer, 2003). This shows that the objects that are selected into the focus of attention are not specific contents—when an item is updated, its content changes, but the object held in the focus remains the same, so that updating the same object again is faster than updating another object in the set. What remains constant across successive updates is the context by which the different items are distinguished and addressed (for instance, their boxes). Thus, what is selected by the focus is not the representation of a digit in semantic memory, but an episodic memory object defined by whatever is currently bound to a specific context, and this object maintains its identity across changes of its content. In this regard, objects in the region of direct access are similar to the *object files* in perceptual attention (Kahneman, Treisman, & Gibbs, 1992).

2.2. Procedural Working Memory

So far I have been concerned only with the representation and selection of the contents of cognitive activity, not the representation and selection of the cognitive operations themselves. I venture that the procedural part of WM can be conceptualized largely analogous to the declarative part, that is, as three embedded components that reflect three successive levels of selection of representations. A sketch of the architecture of WM, augmented by the procedural part, is given in Figure 4.

The representations in the procedural part are procedures. Procedures can be defined as (cognitive or motor) actions linked to the conditions in which they can be applied, and to the expected outcomes. Procedures form networks of associations in LTM, linking them sequentially and hierarchically to action plans (Schneider & Logan, 2007), and linking similar or

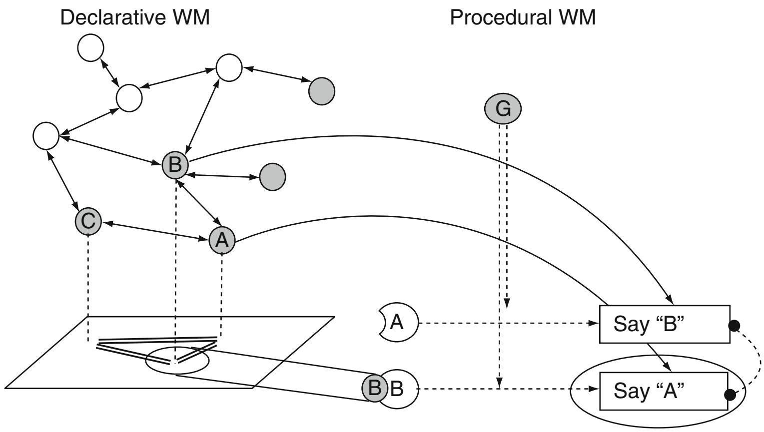

Figure 4 *Architecture of declarative and procedural working memory*. For explanation of the declarative side see Figure 1. On the procedural side, two condition–action bindings are illustrated that link representations of condition categories A and B to the response of saying "B" or "A," respectively. These bindings implement the goal (G) to establish an incompatible stimulus–response mapping (i.e., saying "B" in response to A, and saying "A" in response to B). The two responses are connected by mutually inhibitory bindings (dotted line with nob ending). Together, these bindings constitute the current content of the bridge. The compatible mapping is represented by associations (bowed thin continuous lines) from declarative elements in LTM to the corresponding response representations; these associations are instances of procedural long-term memory. Executive processes, represented by thin broken lines, mediate between the goal G (which could be paraphrased as: "respond to each letter by saying the other letter") and the task set implementing it. In the present state of the system, the declarative element B is selected by the focus of attention. It matches the condition of one stimulus–response mapping in the bridge. The response bound to it is selected by the response focus (the second large oval).

equivalent procedures to each other. A subset of procedures is activated at any time; they form the *activated part of procedural LTM* (for evidence supporting the persistent activation of procedures in LTM see Woltz & Was, 2007). Procedures can be activated by representations of goals that they serve, as well as by stimuli to which they have been applied in the past (Waszak, Hommel, & Allport, 2003).

Activated procedural representations compete for control over a more central component of the procedural system, which I call the *bridge* (as in command bridge,[2] or as in bridge between stimulus and response). The bridge holds the currently operative task set, that is, the task set that is currently in control of thought and action. A task set is a coordinated set of

[2] One meaning of *bridge* is "the platform on a ship from which the captain and officers direct operations" (Oxford online dictionary, http://www.askoxford.com/).

condition–action–effect bindings (a.k.a. stimulus–response mappings) that specify for a confined set of conditions which action or cognitive operation to undertake, and which outcome to expect. The task set in the bridge is implemented as a set of directly executable procedures, such that whenever one of the conditions is represented in the focus of attention of declarative WM, the corresponding action is automatically executed. Thus, the operative task set acts as a "prepared reflex" (Hommel, 1998b). This procedural representation of a task differs from a declarative representation of the same task as a set of (typically verbal) instructions. Declarative representations of instructions can be instrumental in remembering what to do in which situation (Emerson & Miyake, 2003; but see Bryck & Mayr, 2005), especially early in practice, but I assume that immediate control of (cognitive) action lies with procedural representations, and a declarative instruction can be effective only by guiding the construction of a corresponding procedural representation in the bridge.

The bridge in procedural WM corresponds to the DA region in declarative WM, in that it serves to establish and hold temporary bindings between representations—here: between stimulus, response, and outcome representations. As in the DA region, these bindings are not limited to the learned associations in LTM. New bindings can be quickly and flexibly set up to link any stimulus category to any arbitrary response, for instance, to implement an experimental instruction. These bindings enable direct access from the stimulus to the response category (and its expected effect), as long as the particular set of bindings is upheld. The ability to form arbitrary *ad hoc* bindings between mental objects and cognitive operations on them is crucial for the flexibility of our thinking—we can make our responses to what we represent in declarative WM depend not only on the content of those representations but also on our current goals and intentions.

Finally, in the same way as the declarative WM system needs a mechanism for selecting a single object, the procedural system needs a mechanism for selecting a single (cognitive) action at any time. Corresponding to the focus of attention for objects, we must assume that the selected response attains a status that sets it temporarily apart from the competing responses in the task set. I will refer to this mechanism as the *response focus*.

The set of condition–action–effect bindings established as prepared reflexes in the bridge must be coordinated such that the conditions are mutually exclusive categories, each of which is uniquely mapped to a different action. This coordination is necessary to avoid cross talk from alternative mappings that could process the same objects as input but result in different, often incompatible operations (e.g., incrementing vs decrementing the population of China in the mental model discussed above). Therefore, the content of the bridge usually is a single task set that consists of a coordinated set of mutually exclusive condition categories, and the actions and effects bound to them. To optimize selection of a single response, inhibitory links are set up between the response alternatives in the task set (Bogacz & Gurney, 2008; Usher & McClelland, 2001).

Tasks and procedures activated in LTM outside the bridge cannot directly control cognitive operations or actions—their responses are not candidates for selection by the response focus. They can, however, influence response selection in two ways. First, if the responses of an activated task set in LTM overlap with those of the task set currently established in the bridge, the former can contribute to *priming* these responses, that is, boost their activation without actually selecting them for execution (for a similar view see Lien & Proctor, 2002). Second, by virtue of being activated, a task set in LTM can be easily retrieved into the bridge (in particular when cued by either a task cue or by a stimulus that fits the condition part of the task set). In that case, the active task in LTM replaces the previous task set in the bridge and takes over control.

Both kinds of effects can be observed, for instance, in the Stroop paradigm: On incongruent trials, when the color word does not match the print color to be named, the irrelevant but strong association between printed words and speaking these words in LTM primes the response to speak the printed word. If the primed response is incongruent with the correct response (e.g., "blue" printed in green), correct responses are slowed because of the time needed to overcome the competition from the activated incorrect response. On some incongruent trials, however, people actually read the color word instead of naming the color. On these trials, the task to read printed words takes over the bridge, so that the unintended task is carried out—Kane and Engle (2003) refer to this as *goal neglect*. Evidence from a number of sources, reviewed by Kane and Engle, suggests that the two effects—slowed correct naming of incongruent colors and increased rate of word reading—are dissociable, consistent with my assumption that activated procedures in LTM can influence processing in two different ways, by priming responses and by displacing the current task set in the bridge.

2.2.1. Evidence for the Components of Procedural Working Memory

Evidence supporting the embedded component structure of procedural WM as outlined above is sparse, because procedural WM has rarely been addressed directly by empirical studies. Much work on perceptual attention and action selection, however, is relevant for procedural WM. In drawing on this literature, we must bear in mind one important difference: Whereas in studies of immediate memory, participants encode new content–context bindings with every trial, experiments on action selection typically provide an instruction mapping stimuli to responses at the beginning of the experiment and ask participants to use the same mapping for many trials. I believe that the latter experiments are nevertheless informative for procedural WM, because I assume that even well-practiced stimulus–response mappings must be implemented as task sets in the bridge to control processing, in the same way as well-learned declarative associations in LTM must be projected into the DA region and maintained there by temporary bindings to be accessible for processing. Nevertheless, in typical experiments on action selection that use constant stimulus–response mappings it is difficult to rule out the theoretical alternative that, after a few initial practice trials, response selection is executed merely through gradually strengthened stimulus–response associations in LTM.

For this reason, a recent series of studies by Cohen-Kdoshay and Meiran (2007) is particularly important for bridging between the research traditions on WM and on action selection. These authors looked at the first few trials after instructing a new set of stimulus–response mappings and found that stimuli activated their corresponding responses automatically. This finding supports the idea that the task set is implemented as a set of ''prepared reflexes'' in WM, using *ad hoc* bindings between stimuli and responses, rather than emerging from gradual strengthening of associations in LTM over many trials. Thus, the concept of the bridge as a mechanism for *ad hoc* binding on the side of procedural WM, analogous to the DA region on the declarative side, gains some plausibility, although much more work is necessary to establish it firmly.

From the heuristic assumption that declarative and procedural WM work according to analogous principles we can make the prediction that the analogous components of both systems should show analogous empirical signatures. Table 2 lists the empirical signatures that I offered as evidence for the components of declarative WM above, and aligns them with corresponding phenomena in the domain of procedural WM. If this analogy holds, we should expect the following three empirical signatures in procedural WM: (1) Set-size effects should be observed for the number of stimulus–responses bindings held simultaneously in the bridge, but not for stimulus–response mappings in task sets merely activated in LTM. (2) Switching between task sets takes time, and these switch costs increase with the set size of the task set switched away from, but not with the set size of the new task set. (3) Repeating a response selected previously should be faster than switching to a new response. A fourth prediction, which so far has no direct analogue on the declarative side, can be derived from the assumption that the response focus holds only one response representation at a time: Procedural WM can select only one response at a time, and this limitation creates a bottleneck for cognitive operations. I now discuss evidence for these four predictions (the evidence for the first two is closely linked, so I discuss it jointly in the following section).

2.2.1.1. Set-Size Effects for Stimulus–Response Mappings and Task-Set Switching Costs Relevant evidence for the first two predictions comes from the task switching literature (for a review see Monsell, 2003).

Table 2 Analogous Phenomena in Declarative and Procedural Working Memory.

Phenomenon	Declarative WM	Procedural WM
Set-size effects	Set-size effect for relevant set of objects in DA region No set-size effect for currently irrelevant set in activated LTM (Oberauer, 2002)	Set-size effect for number of S–R bindings in operative task set in the bridge No set-size effect for currently not operative task set (Hübner et al., 2004)
Switching structural representations	Costs for switching between lists of items Lists-switch costs increase with set size of old list but not with set size of new list (Oberauer, 2005b)	Costs for switching between task sets Switch costs increase with number of S–R bindings in old task set but not with number of S–R bindings in new task sets (partial support in Hübner et al., 2004)
Switching focus	Switch costs for focusing on new object, increasing with set size in DA region (Oberauer, 2002, 2003)	Response switch costs (Bertelson, 1965)
Serial selection	Only one object can be selected into the focus at the same time	Only one response can be selected at the same time (Pashler, 1994), but there are exceptions (Oberauer & Kliegl, 2004)

When people switch between two tasks, only the currently relevant task set is held in the bridge, other task sets that were recently used and are expected to be used in the near future will be activated in procedural LTM. Switching from one task set to another involves removing the old task set from the bridge, and retrieving a new task set from LTM (Mayr & Kliegl, 2000). Task-switch costs reflect to a large degree the time for this process.[3]

One important distinction between activated LTM and the DA region in declarative WM is that only representations in the DA region compete for selection into the focus, and therefore, set-size effects on access latencies are found only for the set in the DA region, not for any additional sets held in activated LTM. By analogy, we should expect a set-size effect for the number of stimulus–response mappings in the currently selected task set, but not for other active but not selected task sets. There is no study directly addressing this prediction, but some relevant evidence can be found in a couple of experiments by Hübner, Kluwe, Luna-Rodriguez, and Peters (2004). In their Experiment 1A, people switched between a task set with two stimulus–response mappings and a task set with four mappings. Unsurprisingly, reaction times were about 200 ms longer in the task with four mappings. In Experiment 1B, people switched between two tasks, both of which had four mappings. Reaction times were about as large as in the four-mapping task of Experiment 1A (although no formal comparison was made between experiments). Thus, the number of mappings of the relevant task set—which must be established in the bridge—had a large influence on reaction times, but the number of mappings in the currently irrelevant task set—which arguably is held activated in LTM, but outside the bridge—has little or no effect on reaction times.

Task-switching situations typically engender a general cost from holding more than one task set ready for use, compared to a situation where only a single task set is relevant for a whole block of trials. These "global switch costs" or "mixing costs" could be thought of as evidence against the contention that only one task set is held in the bridge at any time in task-switching paradigms. Rubin and Meiran (2005), however, have shown that mixing costs do not reflect an increased load on a limited-capacity WM. If all task sets involved in a switching experiment added to the load on the bridge, increasing the number of task sets should increase mixing costs. This was not the case in Rubin and Meiran's study (for further evidence see Kray, Li, & Lindenberger, 2002). Mixing costs increased, however, when the stimuli were "bivalent," that is, not only the currently relevant but also the currently irrelevant task set(s) could be applied to them. This suggests that the currently irrelevant task sets are maintained outside the bridge, but in a

[3] Task-switching costs have been decomposed into several components (Meiran, Chorev, & Sapir, 2000). I use the term task-switch costs to refer to the difference between switch trials and no-switch trials on mixed blocks at short cue-stimulus intervals (i.e., "switching costs" in the terminology of Meiran et al., 2000, p. 248).

highly activated state that makes them easy to retrieve back into the bridge, in particular when they are cued. Other experiments have shown that stimuli fitting the conditions of the condition–action links in a task set act as retrieval cues for these task sets when they have been used recently (Waszak et al., 2003). Mixing costs could thus be interpreted as arising from occasional inadvertent retrieval of a currently irrelevant task set into the bridge, or from the extra time it takes to prevent such retrieval. When the responses of the task sets overlap, priming of the wrong responses along stimulus–response associations outside the bridge can additionally contribute to mixing costs—this factor seems to play a significant role particularly in older adults (Mayr, 2001).

Further evidence for the assumption that only relevant responses contribute to response competition comes from experiments with the Stroop paradigm (for a review see MacLeod, 1991). Color words interfere with naming the word's ink color only if the word refers to a color that can also occur as an ink color. This finding can be explained by assuming that the bridge holds stimulus–response mappings only for the colors that are expected to occur as ink colors. Color words not occurring as ink colors therefore cannot prime a response that belongs to the selection set in the bridge. Roelofs (2001) reviews results with a variant of the Stroop paradigm, picture naming in the context of interfering words. When the set of pictures used is small and frequently repeated, words not in that set do not interfere. With a large and rarely repeated set of pictures, however, all words interfere with picture naming. Roelofs explains this observation by assuming that a selection set of responses can be maintained in short-term memory only when it is sufficiently small and frequently repeated. In the present framework, this "short-term memory" would be the bridge of procedural WM. But why does any word interfere with picture naming when the set of pictures is large? In such a situation, the task set in the bridge cannot specify all stimulus–response mappings individually. Rather, the task set must include a call to declarative LTM. Expressed as a verbal rule, the task set would be "If a picture is presented, retrieve its name from LTM and say it aloud." Interference from the distracting word arises because the word activates a corresponding representation in declarative LTM, which interferes with the retrieval of the name for the picture.

I assume that set-size effects in the central components of WM—the DA region and the bridge—arise not only from competition for selection, but also from representational interference. The latter causes increasing degradation of representations with larger set size, such that only a limited number of elements can effectively be held in the central components at any time. Whereas there is plenty of evidence for such a capacity limit for declarative WM, there is very little on the procedural side. Some initial support for a capacity limit on procedural WM comes from a study by Ellenbogen and Meiran (2008). They created a dual-task situation in which two speeded choice tasks had to be performed in rapid succession, and the response of the second task (saying a color word) could be compatible or incompatible with the stimulus of the first task (classifying the stimulus by its color). In dual-task setups like this, *backward compatibility effects* are frequently observed (Hommel, 1998a), showing that the response to the second task is at least activated before the response to the first task is selected. Ellenbogen and Meiran hypothesized that in this case, the cognitive system tries to hold both task sets simultaneously in a capacity-limited WM. Doing so would be more difficult, however, when the load on WM by the first task is raised by increasing the number of stimulus–response mappings. Ellenbogen and Meiran therefore predicted that the backward-compatibility effect should disappear, and this is what they found when they increased the number of mappings in the first task to six.

The finding of Ellenbogen and Meiran (2008) can be contrasted with the finding of Kiesel, Wendt, and Peters (2007) in a task-switching paradigm in which both tasks are mapped to the same set of response alternatives. In this paradigm, congruent stimuli that are mapped to the same response by both tasks are typically responded to faster than incongruent stimuli that are mapped to different responses by the two tasks. Kiesel et al. found that this *congruency effect* was not diminished by increasing a concurrent load on declarative WM. The congruency effect was modulated, however, by the relative frequency of stimulus–response pairings in previous trials. These results suggest that, different from dual-task paradigms, task-switch paradigms do not encourage people to hold two task sets in the bridge at the same time; rather, congruency effects in task switching reflect the strengthening of stimulus–response associations of both tasks in LTM, such that each stimulus primes the responses for both tasks. Further evidence that the congruency effect arises from task sets that are activated in LTM has been obtained by Meiran and Kessler (2008). They showed that the congruency effect occurs only if the task set creating involves an abstract representation of the response categories (e.g., "up," "down") that is well established in LTM either preexperimentally or through training within the experiment. When no such representation exists in LTM, none can be activated, and without mediation through an activated abstract response code the stimulus representation cannot prime the corresponding response.

The second empirical signature derived from the analogy with declarative WM includes the prediction that task-switch costs depend on the set size of the task set switched away from, but not on the set size of the task set switched to. Some evidence supporting this prediction can again be found in the experiments by Hübner et al. (2004). They asked people to switch between a task with few stimulus–response mappings and a task with many stimulus–response mappings and found that task-switch costs were smaller when switching to the task with the larger number of stimulus–response mappings. In these experiments, switching to a task set with more mappings implied switching away from a task with fewer mappings, so these findings are at least consistent with the hypothesis that switch costs increase with the set size of the task switched away from, and not with the set size of the task switched to. A direct test of this hypothesis would require fully crossing the set sizes (i.e., number of mappings) of both tasks, analogous to my experiments on list-switch costs (Oberauer, 2005b).

In the context of set-size effects in procedural WM, and the capacity-limiting factors they reflect, the work of Duncan and colleagues on *goal neglect* is also relevant (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Duncan et al., 2008). In their paradigm, participants see a series of pairs of stimuli (e.g., two letters), each screen displaying one stimulus on the left and one on the right side. Participants must respond to the stimuli on one side only (e.g., name the letter on the left side). At some point in the series, a symbol is presented centrally instead of a pair of letters, and this signals a side change; from now on the letters on the right side must be named. The whole series is presented at a fast pace. Goal neglect is demonstrated when people ignore the side-change stimulus, thus continuing to respond to the stimuli on the same side as before. Goal neglect occurs even when people can recall at the end of the experiment the instructions on how to respond to the side-change stimulus. This finding implies that goal neglect does not simply arise from forgetting of the relevant instruction. Further, general intelligence is negatively correlated with the frequency of goal neglect.

Duncan et al. (2008) showed that the probability of goal neglect depends not on the complexity of the main task actually conducted, but on the complexity of the task that people are instructed and given practice on. For instance, in their Experiment 3 one group of participants was instructed, and given brief practice with, a task-switching protocol by which they alternated between reading letters and adding digits on the relevant side of each screen, whereas another group was initially instructed on only one of these tasks. After the practice trials both groups were told that they were going to work on only one task (e.g., only letter reading). The group initially instructed on the task-switching protocol committed more goal neglect. Duncan et al. interpret their results as evidence for a capacity limit on the ability to establish a *task model* based on instructions. When the task model's complexity exceeds capacity, it is simplified by dropping some part of it, for instance, the side-change rule.

In the framework I propose here, Duncan's goal-neglect paradigm can be understood as a task-switching paradigm. Work on each trial starts with the task set for the main task (e.g., letter reading) in the bridge. When the side-change symbol comes up, people must rapidly switch tasks, that is, retrieve the side-change task set from procedural LTM into the bridge; execution of that task set shifts visual attention to the other side. On this analysis, goal neglect can be understood as a failure to retrieve the task set for the side change. Given the high time pressure in this paradigm, such failure becomes more likely in people who process the main task more slowly, because they will still be busy completing the last operation of the main task when the side-change symbol appears, and because general intelligence is correlated with processing speed, this can explain the correlation of goal neglect with intelligence. Successful retrieval of the side-change task set also depends on an association between the retrieval cue (i.e., the side-change symbol) and the task set, which can be established during the practice trials, or through mental practice in response to the instructions. The effect of instruction complexity could arise because people who received more complex instructions suffer from more representational interference in the bridge during practice and therefore are less likely to accomplish the practice trials correctly. In particular, they are less likely to do the side-change correctly in the practice phase. As a consequence, they have weaker associations between the side-change symbol and the side-change task set, and thus are more likely to commit goal neglect.

2.2.1.2. Response-Switch Costs It has long been known that repeating the same response in a series of choice reaction-time tasks results in a benefit of about 100 ms, even when the stimulus triggering that response changes between trials (Bertelson, 1965). This response-repetition benefit, or response-switch cost, can be regarded as the analogue to object-switch costs, or object-repetition benefits, in declarative WM. Response-repetition benefits seem to be smaller than object-repetition benefits, and they do not last long, suggesting that the response focus does not hold on to a response representation after it has been executed as long as the focus of attention holds on to a declarative representation after it has been used in a cognitive operation.

Recent research on the response-repetition benefit has revealed that it disappears, or is even reversed, when the task set used to select the response, or the stimulus category demanding the response, is changed (Kleinsorge, 1999; Schuch & Koch, 2004). These findings imply that the representation held in the response focus cannot be a representation of the physical response (e.g., a motor program or an action plan) but rather must be a representation of the "meaning" of the response (Schuch & Koch, 2004). For instance, when an odd–even judgment on digits is followed by a large–small judgment, pressing the left key could mean "odd" on the first trial, but mean "large" on the second trial. Therefore, repeating the same physical response does not incur a repetition benefit. I conclude from these findings that the representation in the response focus is a representation of the decision or conclusion that the procedural system has arrived at by processing a declarative representation through the currently operative task set. That decision or conclusion can be, but does not have to be, linked to a physical action. A physical action resulting from a decision, and its expected outcome, must be part of the task set that controls overt actions, and there must be a mechanism to select the appropriate physical action over competing alternatives, but that mechanism apparently does not hold on to the selected representation after its execution, and therefore does not give rise to repetition benefits for the actions themselves when their meaning changes.

2.2.1.3. Response-Selection Bottleneck The fourth prediction motivated by the analogy between declarative and procedural WM is that the response focus selects only one response at a time. Evidence for this prediction comes from the dual-task literature, which strongly points to the existence of a response-selection bottleneck for even very simple choice tasks (Byrne & Anderson, 2001; Pashler, 1994). Evidence for a bottleneck also exists for purely cognitive operations that update representations in WM (Oberauer & Göthe, 2006). The evidence that objects in declarative WM can be updated only one at a time suggests that not only responses in the response focus but also objects in the focus of attention are selected one at a time, thus providing preliminary evidence for a bottleneck on object selection that is analogous to the bottleneck on response selection (see the bottom-left cell of Table 2).

Neither the presumed object-selection bottleneck nor the response-selection bottleneck, however, is immutable. Using a memory-updating paradigm similar to that of Oberauer and Göthe (2006) but with reduced memory load, my colleagues and I found that young adults (but not old adults) can, with substantial practice, acquire the ability to update one digit and one spatial position in WM simultaneously without mutual interference between these processes (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004).

The theoretical framework developed here provides some guidelines for explaining why, and under which circumstances, overcoming the selection bottlenecks should be possible. The bottlenecks are assumed to arise not from hard-wired architectural constraints but from the functional constraints on the attentional mechanisms in WM. The function of these mechanisms is to unambiguously select an object for processing in declarative WM, and a response in procedural WM. Limiting the contents of the two foci to a single representation is a straightforward way of avoiding selection ambiguity, and likewise, limiting the content of the bridge to a single task set is an effective way of avoiding cross talk between task sets (cf. Logan & Gordon, 2001). These constraints, however, can be relaxed in situations where ambiguity and cross talk are highly unlikely. A digit and a spatial position are unlikely to be confused. Moreover, in our experiment people only held one digit and one spatial position in declarative WM at any time, thus minimizing the selection demand on the focus of attention because of a lack of competitors. Under these conditions, the focus of attention can hold a digit and a spatial position jointly without creating selection ambiguity. Likewise, an arithmetic computation and a shift of an object in space are unlikely to create cross talk because the shift cannot be applied to the numerical value of the digit, and the spatial location cannot be affected by an arithmetic operation. Therefore, the system can, with sufficient practice on the specific task combination, learn to relax its default cautionary setting and hold two objects in the focus of attention and two task sets in the bridge, and select two responses into the response focus simultaneously.

According to this view, whether parallel processing is possible depends not on the individual tasks but on the distinctiveness of representations and processes in a task combination. Consistent with this view, practice on the task combination, not practice on the individual tasks, enabled parallel processing (Oberauer & Kliegl, 2004). Moreover, in an unpublished follow-up study combining the digit updating task with a letter updating task, people could not perform both tasks in parallel even after extended practice (Brambosch, 2003). This finding shows that the distinctiveness of the two task sets is an important prerequisite for acquiring parallel processing.

2.2.2. Executive Processes

Speaking about WM one cannot avoid speaking of executive processes, because the two terms have been so closely linked in the literature. Some use the terms *executive processes* or *executive functions* in a very encompassing way that treats the whole of WM as one instance of them. Nothing is to be gained for an understanding of WM from using that concept. Others use the term *central executive* to refer to the processing mechanism(s) of WM, setting them apart from the storage mechanisms (e.g., Goldman-Rakic, 1997). Used in this way, the term roughly coincides with my concept of procedural WM, and that is why I placed my discussion of executive function in this section. It is worth noting, however, that Baddeley (1986) originally modeled his central executive after the Supervisor Attentional System (Norman & Shallice, 1980), which is meant to supervise and control ongoing cognitive processes rather than execute them itself.

In keeping with the general idea of Norman and Shallice, I find it useful to distinguish between primary processes and executive processes. I call *primary processes* those that take declarative representations (either from perception or from declarative WM) as input and produce manipulations of declarative representations or overt actions as output. In contrast, I call *executive processes* those that have as their output a manipulation of the conditions of primary processes. Executive processes can change the conditions of primary processes by changing their parameters (Logan & Gordon, 2001), such as changing the speed-accuracy trade-off criterion. Alternatively, executive processes can control primary processes by changing the representations in declarative or procedural WM that guide the primary processes, such as manipulating the activation levels of representations in LTM, and updating the contents of the DA region or the bridge.

Individual-differences research has distinguished three categories of executive function tasks: *updating of WM, inhibition of prepotent responses*, and *task-set switching* (Friedman et al., 2006; Miyake et al., 2000). All three categories of tasks involve establishing a new representation that is necessary for an intended task against a conflicting old representation that is irrelevant or misguiding. Whereas *updating* refers to replacing old representations in declarative WM by new ones, *inhibition* and *switching* refer to establishing new representations in procedural WM in competition with old ones. The difference between inhibition and switching is that inhibition tasks require establishing a new task set in the bridge against a habitual response tendency intruding from procedural LTM, whereas switching requires establishing a new task set against another task set that is currently held in the bridge, but does not necessarily have a strong representation in LTM. Thus, inhibition requires implementing the intended task set in the bridge strongly, so that a highly activated but unintended procedure in LTM is not inadvertently retrieved into the bridge and takes over control. Task-switching involves replacing the current task set in the bridge by a new one; thus, it can be conceptualized as updating procedural WM.

Table 3 presents a proposed taxonomy of demands on declarative and procedural WM, as reflected in tasks used to study WM or executive functions. The common denominator of these tasks is that they require maintaining goal-relevant representations in a state of immediate availability. The representations whose maintenance is performance limiting can be either declarative (in the first column) or procedural (in the second column). The first row includes tasks that are primarily limited by the ability to maintain representations available, without a large role for competition. The tasks in the second row, *Overcoming Competition*, add to this the requirement of overcoming distraction by competing representations that become strongly activated by misleading stimuli, misleading associations, or both. The third row, *Updating*,[4] combines maintenance with the requirement to update representations. This class of tasks is interesting because they focus on a fundamental dilemma of WM, to strike the balance between holding on to representations and replacing them by new ones (Dreisbach & Goschke, 2004; Durstewitz & Seamans, 2002).

The tasks regarded in the literature as reflecting executive functions are found in the second and third row of the table, reflecting *Overcoming Competition* and *Updating*, respectively, in addition to the maintenance demand common to all three rows. The demands in the bottom two rows

[4] I use the term *Updating* in capital letters to refer to the category of tasks in the bottom row of Table 3, which involve updating of either declarative or procedural WM, and *updating* in lower-case to refer to the updating factor in Miyake et al. (2000), which includes only updating of declarative WM.

Table 3 Taxonomy of Demands on WM.

Demands	Declarative WM	Procedural WM	Common required function
Maintenance	Short-term recall or recognition *Digit span, Sternberg recognition paradigm*	Hold new task set to guide action *Speeded choice RT with arbitrary S–R mapping*	Activation, binding
Maintenance + Overcoming competition	Overcoming proactive interference from LTM *PI paradigm, recent probes task,*[a] *modified Sternberg task,*[b] *storage + processing paradigms*[c] *(?)*	Overcoming prepotent responses ("inhibition") *Stroop task, antisaccade task*	Strong binding, executive processes
Maintenance + Updating	Replacing old contents of declarative WM by new ones ("updating") *Keep-track,*[d] *memory-updating*[e]	Replacing old task sets by new ones ("switching") *Task-set switching paradigm*	Flexible binding and unbinding, executive processes

Note: Example tasks are given in italics; brief descriptions of not commonly known tasks follow.

[a] The recent-probes task is a variant of the Sternberg recognition task in which negative probes of the current trial were included in memory lists on recent trials, thus producing misleading familiarity.

[b] In the modified Sternberg task, participants encode two lists, one of which is post-cued to be forgotten. Recognition probes from the to-be-forgotten list create misleading familiarity.

[c] Storage + processing paradigms (e.g., reading span, operation span) combine immediate recall of short lists with episodes of a typically unrelated processing task either in between or after presentation of list items. The status of storage + processing paradigms is uncertain: If the concurrent processing task leaves traces in WM that compete for recall with the to-be-remembered list items, the task reflects overcoming competition; otherwise it just reflects maintenance.

[d] In keep-track, participants see a list of nouns and must remember the last noun in each of a number of categories.

[e] In memory updating, participants remember several digits and update them individually by arithmetic operations.

have in common that they require the frequent intervention of processes that take goal representations as input and generate strong goal-appropriate representations in WM as output, in other words, executive processes. There is, however, an important difference between *Overcoming Competition* and *Updating*: Performance in tasks that require overcoming competition must be assumed to depend on two factors, the effectiveness of executive processes in establishing the goal-relevant representation, and the ability of the WM system to hold and maintain strong bindings that can overcome prepotent memories or response tendencies from LTM. The ability to maintain strong bindings is, in my view, the main limiting factor of WM capacity. Thus, tasks measuring the ability to overcome competition reflect a mixture of two variables, the efficiency of executive functions and the capacity of WM. In Updating tasks, in contrast, having high WM capacity is unlikely to be helpful. A person with high capacity would have the disadvantage of having to overcome strong bindings to remove the old content of the DA region or the bridge, but the advantage of being able to strongly bind the new content. A person with low capacity would have to overcome weaker bindings with a weaker mechanism to establish new bindings. There is no reason to assume that one or the other will be more effective in updating. In other words, whereas in overcoming-competition tasks, the WM system fights conflicting tendencies from external sources, in updating tasks, WM fights itself. Therefore, Updating tasks could be regarded as a relatively pure reflection of executive functions because performance is unlikely to be affected by WM capacity. The only determinant of success in Updating tasks should be the speed and accuracy of executive processes that decide on and carry out the updating.

Do executive processes have a special status in the cognitive system? One might argue that they do not. In this view, executive processes use the same mechanisms as primary processes, they just happen to have responses that control the cognitive system itself rather than some aspect of the environment. A consequence of this view is that executive processes must share with primary processes the limited capacities of declarative and procedural WM. In particular, the bottleneck in the bridge would force the system to alternate between task-sets for primary processes and task-sets for executive processes. This idea raises the question how the switch between primary and executive task sets is managed—it seems that an executive process is needed to switch from a primary to an executive process. This looks like very bad design.

For an efficient WM system we need to assume that at least some executive functions avail of a separate mechanism that enables them to run in parallel with primary processes, so that they can intervene in primary processes. This assumption is in agreement with theory and data on at least one executive process, stopping an action. Logan and Cowan (1984) analyzed the stop-signal paradigm, in which participants do a speeded choice task and are instructed to stop responding when they perceive a stop signal, which occurs on a minority of trials. Logan and Cowan successfully applied a race model to data from this paradigm in which the primary response-selection process and the stop process run in parallel.

Not all executive processes, however, seem to have the privileged status of being independent of primary processes. Monitoring of one's performance, and correction of errors, can be regarded as a prime example of an executive function. It has long been known that when people commit an error in a series of simple choice tasks, they slow down on the following trials (Laming, 1968). This posterror slowing has been interpreted as reflecting an adjustment of the speed-accuracy trade-off setting to avoid further errors. A recent study by Jentzsch and Dudschig (2009), however, casts doubt on this interpretation. They showed that posterror slowing is more likely a manifestation of a processing bottleneck: After an error, processes interpreting the error and making adjustments occupy the processing bottleneck for some time, thus postponing processing of the next stimulus. It seems that at least some executive processes compete with primary processes for the bridge in procedural WM.

To conclude, an analysis of functional necessities, as well as some empirical evidence, point to the existence of a separate mechanism for executive processes in addition to declarative and procedural WM, such that executive processes can run in parallel with primary processes. This mechanism, however, seems not to be used by all processes that are regarded as executive in the literature, and that match my definition proposed above. Future research will hopefully distinguish between executive processes that must share mechanisms with primary processes and others that do not, and this might provide a more robust basis for classifying cognitive processes than the crude distinction into primary and executive processes that I can offer at this point.

2.2.3. Are Declarative and Procedural Working Memory Separate Systems?

I have assumed so far that, at least for the central components of the WM system, declarative and procedural WM are parallel but separate systems. An alternative is that there is only one WM system that is used for both declarative and procedural representations. Thus, there would be no significant difference between bindings linking memory objects to their contexts, and bindings linking objects to (cognitive) actions to be performed on them, and the two kinds of bindings would share the same limited capacity, that is, they would interfere with each other. Moreover, there would be a single focus of attention that selects a composite of a mental object and an associated cognitive operation to be performed on it. Thus, objects and operations would not be selected independently but as tightly packed units. This latter view is suggested by the Theory of Event Coding (Hommel, Müsseler, Aschersleben, & Prinz, 2001), which proposes that perceived objects and events and the actions we perform (or plan to perform) on them are represented as integrated *event codes*.

One straightforward prediction of the independence assumption is that increasing the load on declarative WM should not affect the efficiency of executing a task set held in procedural WM, and conversely, increasing the load on procedural WM should not impair retention of information in declarative WM. This prediction is complicated somewhat by the fact that, whereas task sets are units of procedural knowledge, task *instructions* are instances of declarative knowledge. Often, in particular for novel and not yet practiced tasks, people hold the (usually verbal) task instruction in declarative WM to back up the task set that implements that instruction. Increasing the load on declarative WM could disrupt memory for the task instruction, and as long as instruction memory contributes to task performance, the latter would be impaired. Likewise, making the task set more complex usually implies making the instruction more complex, and thus a more complex task would create more interference with other contents of declarative WM if the person attempts to hold the task instruction in declarative WM. Therefore, an informative test of the above prediction would have to involve a well-practiced task for the manipulation of procedural complexity, which no longer relies on declarative instructions. Alternatively, a nonverbal WM load that does not interfere with verbal instructions held in declarative WM could be used to manipulate declarative WM load. As far as I am aware, no such study has yet been conducted.

Results from individual-differences research turn out to be more informative. Schmiedek, Oberauer, Wilhelm, Süß, and Wittmann (2007) analyzed the relationship between measures of (declarative) WM capacity and reaction times in speeded two-choice tasks with arbitrary stimulus–response mappings. The choice tasks arguably rely at least in part on the robustness of stimulus–response bindings in procedural WM. Schmiedek et al. applied the diffusion model (Ratcliff, 1978) to the reaction time distributions to isolate the decision component from other components of variance in reaction times; the decision component presumably reflects the strength of stimulus–response bindings. In a structural equation model, a latent factor for the decision component correlated highly, but not perfectly, with a latent factor reflecting WM capacity. This finding suggests that the ability to maintain bindings in declarative and in procedural WM share a substantial amount of variance. Further support for this conclusion comes from a study by Wilhelm and Oberauer (2006), who related speed in four-choice tasks with compatible and with arbitrary stimulus–response mappings to measures of (declarative) WM capacity. Choice tasks with arbitrary mappings yielded much larger reaction times than those with compatible mappings. A factor reflecting individual differences in the size of the compatibility effect was highly correlated with WM capacity. This observation is again consistent with the view that there is a common source of variance in the ability to maintain temporary bindings in declarative and in procedural WM. It should be added, however, that a common source of variance does not imply a common mechanism. It is possible that declarative and procedural WM are separate mechanisms that are affected by the same source of individual differences (e.g., global neural noise affecting different neural networks in the same way).

Evidence pointing more toward a distinction between declarative and procedural WM comes from a series of studies of Miyake and colleagues (Friedman et al., 2006, 2008; Miyake et al., 2000). In these studies, the *updating* factor and the *task-set switching* factor were always distinct, though correlated. According to the taxonomy in Table 3, these two factors reflect the *Updating* demand for declarative and procedural WM, respectively. Further, Friedman and Miyake (2004) found that a latent factor reflecting resistance to proactive interference was uncorrelated with their *inhibition* factor. These two factors could be interpreted as representing the *Overcoming-Conflict* demand in declarative and procedural WM, respectively, and their lack of correlation would reflect a dissociation between declarative and procedural WM. The latter result is ambiguous, however, because the proactive-interference measure was obtained from delayed recall tasks that arguably reflect more the robustness of new LTM associations than the robustness of temporary bindings in declarative WM.

A brain-imaging study by Nelson, Reuter-Lorenz, Sylvester, Jonides, and Smith (2003) provides more direct evidence for a dissociation of mechanisms for overcoming conflict in declarative and procedural WM. Using the Sternberg recognition paradigm, they created conflict in declarative WM by presenting probes that were not in the current memory list but in the preceding memory list. These recent negative probes create a conflict between familiarity and recollection. Overcoming the misleading familiarity signal requires strong recollection, which rests on strong bindings between memory items and their list contexts (cf. Oberauer, 2005a). In addition, Nelson and colleagues created conflict in procedural WM by presenting negative probes that were positive probes on the preceding trial, such that the correct response on the present trial conflicts with the correct response on the preceding trial to the same stimulus. Overcoming response conflict arguably requires a strong task set to minimize the influence of the stimulus–response association carrying over from the preceding trial. Nelson et al. (2003) found that conflict between familiarity and recollection increased activation in prefrontal cortex, whereas response conflict increased activation in anterior cingulated cortex. This result suggests that different brain circuits are involved in resolving conflict in declarative and procedural WM.

Overall, there is surprisingly little evidence speaking directly to the degree of independence of declarative and procedural WM. My preference for the assumption of two separate systems, though consistent with extant findings, is motivated mainly on theoretical grounds: Being able to select declarative representations (i.e., the objects of thought) and procedural representations (i.e., our actions on them) independently seems a desirable feature for a WM system, because it enables us to select an object of thought without deciding at the same time on how to mentally manipulate it or how to act on it. Having separate representational systems and selection mechanisms for declarative and procedural representations is a straightforward way of realizing this independence.

3. Working Memory and Long-Term Memory

There is an increasing recognition that the processes attributed to WM are rarely free from contributions from LTM (Burgess & Hitch, 2005; Unsworth & Engle, 2007). In my view, there are two ways in which LTM contributes to the functioning of WM, through activation of existing representations, and through learning of new structural information that can be retrieved back into WM.

3.1. Activated Long-Term Memory

I see three roles of activated representations in LTM for processes that are usually attributed to WM, such as immediate recall or recognition. The first role is to increase the efficiency of processing new stimuli matching already activated representations. This role is manifest in short-term priming (McKone, 1998). In addition, the perceived increase in processing fluency for stimuli matching already activated representations seems to be an important ingredient of their familiarity (Whittlesea et al., 1990).

The familiarity signal generated in response to a stimulus can be used as one source of information for recognition decisions because familiarity is correlated with recency of use. For short-term recognition (i.e., recognition decisions following within seconds after initial encoding of the memory items), processing fluency, and thus familiarity, will be mainly determined by the degree of activation of the memory items in LTM. A further source of information for recognition is recollection, that is, retrieval of episodes of encountering the stimulus before in a relevant context (e.g., the context of the last seen memory list). For short-term recognition, recollection implies retrieving memory items from the DA region, which provides bindings between the items and their contexts. The distinction between activated LTM and the region of direct access receives support by studies of short-term recognition that fit this brief sketch of a dual-process model of recognition (Oberauer, 2001, 2008; Oberauer & Lange, 2009).

A second role for activation in LTM is that activated representations narrow down the search set for reconstruction of memory traces in the DA region. Representations in the DA region can be degraded by representational interference, and in that case retrieval involves recovery of the complete representation by retrieving the best-matching representation in LTM—this form of pattern completion is often referred to as *redintegration* (Lewandowsky, 1999). Having a limited set of activated candidate representations makes redintegration faster and less error prone. Using the ordering of countries by population as a simplified example: Imagine that the representations of countries in the DA region consisted only of their names, and due to interference, at some point the structure consists of degraded memory traces reading: "I_D__, CH__A, R_S___." Matching these traces against the whole vocabulary of the language would make recovery very difficult, but having a search set limited to countries renders the task easier.

A third role for activation in LTM is to provide a limited mechanism for representing serial order. A list of items can be represented in order by imposing a gradient of activation on them, declining from the first to the last. The items can be reproduced in that order by retrieving the one with the highest activation and then suppressing it, thus leaving the next in line with the highest activation. This mechanism has been used in models of forward serial recall of lists (Grossberg & Stone, 1986; Page & Norris, 1998).

Activation gradients, however, are limited in that they do not provide direct access to a specific element—to access the fourth element in a list, for example, retrieval has to proceed from the beginning until it reaches the fourth element. Activation gradients also cannot represent multidimensional structures, such as the location of various elements in two-dimensional space. A powerful mechanism for representing structure requires the ability to establish links between representations. Temporary bindings establish these links in the DA region. To maintain structural representations after they have been removed from the DA region, they must be established in LTM by more permanent associations—and indeed, more is needed than just associations, as I will explain next.

3.2. Structural Information in Long-Term Memory

So far, I have characterized LTM as an associative network of representations. But information in LTM must consist of more than just associations. LTM must be able to retain the specific relations between elements—for instance, who did what to whom when and where in an episode. One of the six requirements of a working memory system is that structural information can be learned over the long term. Associations are not enough to accomplish this. For instance, the fact that the pastor calmed the businessman cannot be represented by associating "pastor," "calm," and "businessman," because that assembly could not be distinguished from one that represents "The businessman calmed the pastor." The representation must specify the kind of relation between the concepts to distinguish different structures involving the same concepts. Thus, LTM must represent structures.

Does this imply that representations in LTM are structural representations? Not necessarily—indeed, structural representations are an inconvenient way of representing structures in LTM. A structural representation means that content components (i.e., objects, events) are linked to their contexts or roles by learned associations. For instance, "pastor" could be associated to the *agent* role in a proposition template, "businessman" to the *patient* role, and "calming" to the *action* role, to represent the fact that the pastor calmed the businessman. It is tempting to think of long-term learning in this way, because then all we needed is a mechanism that copies the bindings in the DA region into corresponding associations in LTM.

This scheme, however, would soon run into trouble when the system learns many more facts and events concerning the pastor and the businessman. Other events to be remembered could, for instance, involve the pastor in the patient role and the businessman in the agent role (e.g., the businessman bribing the pastor). Across all facts and events in memory, each object or concept would be associated to different roles, and each role to numerous objects and concepts, thus creating massive interference. To recover the fact that the pastor calmed the businessman (in one particular time and place), the system needs a mechanism to tell that the association of "businessman" with *patient* belongs together with the association of "pastor" to *agent* (as well as the association of information about time and place to the roles of *time* and *place*). In other words, there must be a mechanism to associate pair-wise content-role associations with each other. Because associations are not themselves representations, it is not obvious how they can be associated together. Therefore, long-term learning of structural information cannot simply consist of translating the bindings in WM into corresponding associations one-to-one.

3.2.1. Chunking Structural Representations

One solution to the problem of acquiring structural representations in LTM is to form unitized representations of structures, which I call *chunks* (Halford et al., 1998; Miller, 1956). A chunk is a representational unit in which other units and their relations are packed so that they are not individually accessible—unless the chunk is unpacked again. Remembering structures as chunks requires that, for every new fact or episode, a new unitized representation must be created. Upon encountering for the first time an episode in which the pastor calms the businessman, the system must create a new chunk representing that proposition. The proposition chunk would be associated with the representations of the three concepts involved (i.e., pastor, calming, and businessman). In addition, it needs to be associated with representations that code the conjunction of each concept with its role in the proposition (i.e., the conjunction of "pastor" with *agent*, of "businessman" with *patient*, and of "calming" with *action*). An illustration of how a relational representation in the DA region of WM is encoded as a chunk in LTM is given in Figure 5A (a similar structure of memory is proposed by Hummel & Holyoak, 2003).

There are several ways in which learning by chunking could be implemented in a neural network. With localist representations (i.e., each content component is represented by a single unit in the network), forming a new chunk means recruiting a new, as yet uncommitted unit to become the new chunk representation (Grossberg, 1987). With distributed representations (i.e., each content component is represented by a pattern of activation across many units), the new chunk could be represented by a new pattern created from its component patterns, for instance, by circular convolution (Jones & Mewhort, 2007; Plate, 2003).

3.2.2. Retrieval of Structural Information from LTM

Figure 5B illustrates how structural information from LTM can be retrieved back into the DA region of WM. The current contents of the DA region serve as retrieval cues for chunks in LTM. Using as cues only the content elements currently bound to some position or role in the DA region, however, would lead to confusion. For instance, when the DA region currently holds a mental model of a businessman calming a priest, the three content elements (priest, calming, and businessman) would cue a chunk representing the proposition "the priest calmed the businessman" and a chunk representing "the businessman calmed the priest" with equal strength. To focus retrieval better on those memories in LTM that match the current contents of thought with regard to their relations, the relations between concepts and roles in the DA region must act as additional cues. For this, the temporary bindings between content and role representations must first be translated into representations that code the conjunction of each concept and its current role. This is the same process as occurs during encoding of a structure as a chunk in LTM. One prediction from this assumption is that, when LTM is cued by a relational cue (e.g., a sentence or a pair of words), retrieval of memories matching the individual elements should be faster than retrieval of memories matching the relation between them, because the latter requires *ad hoc* chunking of the relational information in the cue as an intermediate step. This prediction is confirmed by several studies (e.g., Gronlund & Ratcliff, 1989; Gronlund, Edwards, & Ohrt, 1997; McElree, Dolan, & Jacoby, 1999).

To summarize, I assume that one important difference between the DA region and LTM is that in the DA region, structural information is represented explicitly, that is, by structural representations, whereas in LTM it is packed into chunks. Thus, although LTM contains information much richer than mere associations between ideas, its structure is purely associative—it is a network of associated chunks. Transferring structural

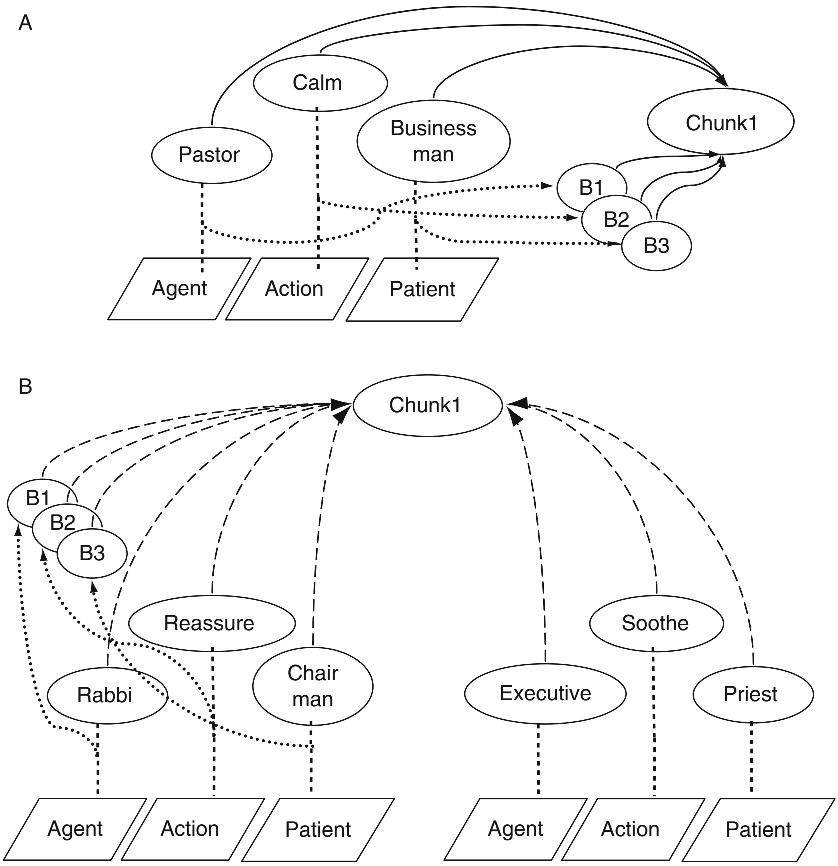

Figure 5 (A) The proposition "The pastor calmed the businessman" is represented in the direct-access region by binding the three concepts (pastor, calm, businessman) to their roles in a proposition template (agent, action, patient). Bindings are represented by thick dotted lines. To encode this proposition into LTM, a chunk is formed that includes information about the concepts, as well as about the bindings of each concept to its role (it is arbitrarily called *chunk1*). The bindings must first be translated into representations (B1 to B3). This conversion is represented by the thin-dotted lines. All representations packed into the chunk (pastor, calm, businessman, B1, B2, B3) are associated to that chunk; associations are shown as continuous lines. (B) When a new proposition is represented in the direct-access region, it cues related chunks in LTM for retrieval. A good analogy such as "The rabbi reassured the chairman" (illustrated on the left) cues *chunk1* with both its concepts and its bindings (again mediated through explicit representations of these bindings, B1 to B3). A bad analogy such as "The executive soothed the priest" (on the right) cues *chunk1* only by its concepts.

information from the DA region into LTM means packing the structure into a chunk. Retrieving of structural information from LTM means cueing a chunk with the current contents of the DA region, and their bindings, and selecting the most strongly cued chunk to be unpacked into the DA region. Unpacking the chunk means to recreate the original structural representation in the DA region. This theory implies that relational information can be maintained in LTM, but it can be accessed for processing only after being projected back into the DA region. The DA region serves as a projection screen of our structural knowledge, thus enabling us to think about structures, that is, extract information about individual relations in a structure and manipulating individual components and relations in that structure.

3.2.3. Evidence for Chunking and Unpacking

Evidence for the mechanisms of encoding structural information into LTM by chunking, and retrieving it by cueing and unpacking, comes from three sources: analogical retrieval, the Hebb effect in list learning, and retrieval times for lists; I will discuss them in turn.

In analogical reasoning, people represent one structure in WM and try to retrieve some knowledge from LTM that matches the structure of the current representation in WM. For instance, when trying to figure out the physics of magma flowing down a volcano, the physics of water flowing down the drain could be a helpful analogue—although its elements differ, its causal structure is similar to the magma problem. Early research on the retrieval of analogues suggested that people are poor at finding structural matches in LTM. Instead, what mostly comes to mind seem to be memories that bear some surface similarity to the problem at hand, that is, similarity between the elements involved regardless of their structure. For instance, when reading a story, people are often reminded of other stories involving the same elements (e.g., the same animals) but rarely of stories that have an analogous causal structure but no shared elements (Gentner, Ratterman, & Forbus, 1993). Later research, however, led to a revision of this picture, showing that retrieval is sensitive to structural similarity between the cues and the to-be-retrieved memory. For instance, Wharton et al. (1994) found that, when given the sentence, "The pastor calmed the businessman," people are more often reminded of a previously read sentence, "The rabbi reassured the chairman" than another previously read sentence, "The executive soothed the priest." The two sentences in LTM have about equal similarity of their elements to the given sentence, but they differ in their structural similarity to the given sentence. Other research shows that analogues can be retrieved on the basis of structural similarity alone, without any similarity between the elements (Blanchette & Dunbar, 2000; Catrambone, 2002). Thus, there is evidence that retrieval from LTM is sensitive to the structure of the cue. This finding supports the assumption that not only the content elements currently held in the DA region, but also their bindings to their context, contribute to the cueing of chunks in LTM.

Evidence for chunking also comes from the literature on memory for lists. Lists can be thought of as structures in which a set of content elements (i.e., list items) is linked to an ordered set of positions. One possible way of encoding lists into LTM is to build long-term associations between each item and its positions. When learning many different lists created by randomly reordering the same items—as in a typical experiment with many trials of immediate serial recall of digit lists—every item will eventually be associated with about equal strength to each position, making LTM virtually useless. However, if some items are placed in certain positions more often than in others, cumulative learning of these item-position associations would help remembering new lists in which the items are placed in these positions (Burgess & Hitch, 1999). This could be an explanation for the Hebb effect (Hebb, 1961): When across a series of trials of immediate serial recall the same list is repeated frequently (e.g., every third trial), performance on the repeated list selectively improves over trials. The explanation of the Hebb effect in terms of pair-wise long-term associations between items and positions, however, has received a serious blow by the finding that there is no cumulative learning when only every second item of a list is repeated in a constant position (Cumming, Page, & Norris, 2003). This and other findings (Hitch, Fastame, & Flude, 2005) have led Burgess and Hitch (2006) to revise their earlier account of the Hebb effect in terms of item-position associations. The revised model assumes instead that each list is remembered in LTM in a unitized form (i.e., a chunk). Repeated lists benefit from long-term knowledge to the degree that their initial items serve as retrieval cues for an existing list chunk in LTM. Thus, data and theorizing on serial recall converge with my analysis above on the conclusion that the representation of structures in LTM requires chunking.

Further evidence for the idea that structures are represented in LTM as unified chunks comes from retrieval times for lists from LTM. Several studies have compared the time for accessing memory lists from WM with the time for accessing the same lists from LTM. Access from LTM takes longer, but the additional time, which is assumed to reflect the time for retrieving a list from LTM into WM, does not depend on the length of the list (Conway & Engle, 1994; Oberauer, 2005b; Wickens, Moody, & Dow, 1981). This finding suggests that a list is retrieved as a single chunk, unpacking of which regenerates the list as a structure in the DA region. The unpacking process itself seems to proceed in parallel because otherwise, longer lists would take more time to unpack.[5]

[5] There are intriguing hints in the literature pointing to the existence of a simpler, purely associative learning mechanism alongside the mechanism for learning structures by chunking that I postulated above (Botvinick & Bylsma, 2005; Majerus, van der Linden, Mulder, Meulemans, & Peters, 2004). The associative learning system would gradually strengthen the association of all representations that cooccur in the DA region, thus picking up the probabilistic structure of the environment (insofar as it is reflected in the representation in the DA region). Exploring the role of this second learning system for the interaction of WM and LTM goes beyond the scope of this chapter.

3.3. Control of Encoding into and Retrieval from Long-Term Memory

Retrieval from LTM means that an LTM representation is projected into the DA region. Conversely, long-term learning means that the contents of the DA region are added to the representations in LTM. The WM system must have a mechanism to control the transfer between these two components. Research on incidental memory (Hebb, 1961; Hyde & Jenkins, 1969) and implicit memory (Graf & Schacter, 1985; Roediger, 1990) shows that every content of thought leaves a trace in LTM by default. Thus, translating the contents of the DA region into a corresponding trace in LTM seems to be the default mode of interaction between these two components.

Conversely, there is much evidence showing that long-term memories influence performance in immediate memory tasks. For instance, the Hebb effect mentioned earlier (Hebb, 1961) implies that memory traces of a repeated list support immediate recall of that list on further trials. Yet, it cannot be the case that any matching LTM content is automatically retrieved into the DA region, because if it was, retrieved information from activated LTM would flood the DA region. As a consequence, every new thought would immediately experience massive interference from many related old thoughts that it reminds us of. In fact, proactive interference is minimal in short-term memory or WM tasks (Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Halford, Maybery, & Bain, 1988; Oberauer & Vockenberg, 2009; Wickens, Born, & Allen, 1963). The WM system must have a mechanism that controls retrieval from LTM into the DA region to avoid proactive interference from LTM.

One solution, of course, is to shield the DA region against LTM by default, and open the gate for retrieval only on demand (i.e., triggered by a goal to retrieve long-term knowledge). This solution, however, would most of the time cut off ongoing cognitive processes from virtually all potentially relevant background knowledge. As a result, our mind would operate like a conventional computer that operates on a small set of representations in its current "work space," and is equipped with an entirely passive knowledge base, the contents of which must be retrieved by active search. Such a system encounters what has become known as the "frame problem" (Pylyshyn, 1987), that is, the problem of how to find, within reasonable time, the relevant information for the problem at hand in a vast data base.

Therefore, I think a more promising solution is to keep the gate between the DA region and LTM open by default, so that activated contents of LTM always have a chance to be retrieved and thereby to influence ongoing processing. Continuous interaction between the contents of the DA region and LTM does not, of course, in itself solve the frame problem; rather, it is an architectural feature that arguably provides a better basis for a solution (cf. Shanahan & Baars, 2005): The contents of the DA region continually activate representations in LTM that match them or are otherwise associated with them, and activated representations in LTM continuously compete for being retrieved into the DA region. Thus, in most cases, the associative network of LTM takes part in the information processing loop to some degree, as I will elaborate in Section 4.

This assumption means that retrieval from LTM is ‘‘automatic’’ in the sense that it can occur without being intended. It is not clear yet whether retrieval is also ‘‘automatic’’ in the sense of not competing with other processes. Tasks testing retrieval from LTM have been found to compete with other concurrent cognitive operations in dual-task studies (Carrier & Pashler, 1995; Craik, Govoni, Naveh-Benjamin, & Anderson, 1996). In these studies, however, the retrieval task always involved an overt response reporting the retrieved information (e.g., saying aloud the word associated to a given cue, or making an old-new decision by pressing one of two keys in a recognition test). Therefore, it is difficult to tell from the existing evidence whether the locus of dual-task interference was the process of retrieving information from LTM into (declarative) WM, or the selection of a response to report that information. Because I assume that the response focus can hold only one response representation at a time, I would predict competition between overt retrieval and other concurrent tasks at response selection. This assumption could also explain why in dual-task studies of retrieval it is the secondary task that suffers, whereas retrieval is protected (Naveh-Benjamin, Craik, Perretta, & Toney, 2000). This would be expected if retrieval itself is not impaired by the secondary task at all, only its report disrupts or postpones the concurrent secondary task.[6]

Returning to the problem of controlling retrieval from LTM, a flexible solution is to put a threshold on the level of activation any LTM representation must attain to be retrieved into the DA region. That threshold could be adapted to the present processing goal—by lowering the threshold, the system could call for relevant knowledge in LTM, and by raising the threshold, it could ask not to be disturbed by intrusions from LTM. Adjusting this threshold to task demands must be regarded as one of the key executive functions regulating WM processes. In Section 4, I will discuss its role in striking the balance between an analytic and an associative mode of information processing.

[6] Carrier and Pashler (1995), using a variant of the PRP paradigm, argued that their findings cannot be explained by interference merely at the response selection stage because they found an additive effect of retrieval difficulty with their manipulation of stimulus–response asynchrony. I do not find this argument convincing, because it depends on the assumption that retrieval and response selection are distinct processing stages, and the difficulty of retrieval has no effect on the duration of response selection. I find it more plausible that their manipulation of retrieval difficulty affected the strength of the retrieved information, which translates into the rate at which evidence accumulates during response selection (Ratcliff, 1978).

4. Analytic and Associative Information Processing

The architecture of WM as outlined so far affords the implementation of two different modes of information processing. The central components of declarative WM—that is, the region of direct access and the focus of attention—together with the central components of procedural WM—that is, the bridge and the response focus—constitute what I call an *analytic processing subsystem*. It is complemented by an *associative subsystem* that consists of the activated part of LTM, including both declarative and procedural representations, which are not as strictly separated in (activated) LTM as they are in the central components of WM.

The distinction between analytic and associative kinds of processes has been noticed and discussed by several authors in the psychology of reasoning (Evans & Over, 1996; Sloman, 1996; Stanovich & West, 2000). Many of these theorists promote the distinction from one between processes to one between systems. The two systems go by various names, but the most common ones today are *System 1* and *System 2*. *System 1* is characterized as associative, intuitive, heuristic, fast, and automatic. *System 2* is thought of as analytic, deliberative, effortful, slow, controlled, and dependent on limited resources of WM (see Evans, 2008, for a review). I prefer to speak of analytic and associative processing modes, because I see them as the end points of a continuum, and they arise not from separate self-contained systems but from interacting sub-systems of WM.

The difference between the two processes or systems has been described by lists of contrasting features that are only loosely conceptually related. Here I make a more principled proposal based on the theory of WM outlined above. The analytic processing mode is characterized by three key features that distinguish it from the associative mode. First, it relies primarily—in the extreme case, exclusively—on declarative representations in the DA region, and procedural representations in the bridge, excluding influences from activated LTM. Second, it operates on representations with low dimensionality. Third, it enables independent selection and manipulation of declarative and procedural representations. I will elaborate on these three features below.

4.1. Shielding Central Working Memory Against Long-Term Memory

In the analytic mode, the central components of WM are shielded against the more peripheral component, that is, the activated part of LTM. This can be achieved by raising the threshold for retrieval from LTM, and by establishing strong bindings in the DA region and the bridge that cannot easily be replaced by activated LTM representations. On the declarative side, these control measures ensure that processing draws only on a confined set of information held in the DA region. For instance, for a deductive inference, the reasoner should draw only on the information given in the premises, and refrain from taking his or her beliefs about the subject matter of the argument into account. People have difficulties narrowing their reasoning processes in this way—when asked whether a conclusion follows with logical validity from given premises, their judgments are strongly influenced by whether or not the conclusion matches their beliefs (for review see Klauer, Musch, & Naumer, 2000), and whether or not a counterexample to the conclusion is available in their knowledge base (De Neys, Schaeken, & d'Ydewalle, 2003; Markovits & Quinn, 2002). The degree to which deductive reasoning is shielded from knowledge in LTM is a function of intention and ability: The influence of knowledge can be reduced, but not completely eliminated, by strengthening the instruction to reason deductively (Vadeboncoeur & Markovits, 1999). Moreover, people with higher WM capacity are more successful in suppressing the influence of knowledge in cases where it conflicts with the logically correct answer (De Neys, 2006). These findings confirm the assumption that retrieval of knowledge associated with the current contents of the DA region is the default mode of processing, which needs to be actively prevented when the task demands exclusive reliance on a confined set of information represented in the DA region. Nevertheless, people can to some degree decouple their thinking from their factual knowledge to engage in counterfactual or hypothetical reasoning. Setting a high threshold for retrieval from LTM enables us to use the DA region as a blackboard for building new structural representations without suffering debilitating interference from potentially conflicting long-term memories or knowledge.

Similarly, on the procedural side, the analytic processing mode means that the selection of actions in response to perceived stimuli or to WM contents is determined by the task set in the bridge alone, which implements potentially arbitrary stimulus–response mappings, and suffers little or no bias from stimulus–response associations in LTM. Moreover, strong competing procedural representations in LTM cannot easily take over the bridge and wrest control from the currently implemented task set. Again, the degree to which processing is analytic can be controlled in response to task demands and characteristics of the environments. For instance, in the Stroop task, people can adjust the relative influence of two competing procedures, one supported by a strong LTM association (word reading) and one implementing the instructed task (color naming) in the bridge. When the proportion of incongruent trials is low, people allow a stronger contribution from word reading, compared to when the proportion of incongruent trials is high (Kane & Engle, 2003). As in the case of deductive reasoning, the degree to which processing is shielded from LTM influences depends not only on the executive processes that adjust the retrieval threshold according to intentions and task demands, but also on the ability of the person to implement strong stimulus–response bindings in the bridge. For instance, in conditions with a low proportion of incongruent trials, people with low measured WM capacity suffered larger Stroop interference effects than those with high WM capacity (Kane & Engle, 2003).

4.2. Dimensionality of Representations

The assumption that analytic processing relies on representations with low dimensionality follows from my characterization of the DA region as providing a mental space in which representations of objects and events can be bound to positions. The dimensions of this mental space can be used to represent relations on any dimension, including physical space, time, and a host of feature dimensions, but the mental space is likely to have a limited number of dimensions—probably not more than two or three. Thus, the relations between elements in the DA region will be limited to a small number of dimensions. For instance, when the relative population sizes of China, Russia, and India are represented by placing the three countries on different points along a dimension of mental space, this representation selectively highlights one feature dimension, population size, while occluding all other features that we know these countries to have.

This contrasts with the representations of concepts, objects, and events in LTM, which can be characterized as points in a high-dimensional space (Jones & Mewhort, 2007; Landauer & Dumais, 1997), reflecting a wealth of knowledge by which we can distinguish them from each other. The dimensions of this "hyperspace" typically do not correspond to nameable feature dimensions. Projecting concepts, objects, or events into the region of direct access creates a low-dimensional representation in which a small subset of dimensions becomes explicitly represented by the dimensions of the mental coordinate system. Operating on representations in the DA region therefore implies focusing on a small number of feature dimensions, ignoring all other features of the represented entities. In contrast, processes that involve LTM representations directly draw on all feature knowledge linked to those representations in an unselective way.

The difference in dimensionality of representations entering analytic and associative processes is most evident in comparisons. Perceived stimuli, as well as representations held in the focus of attention, can be compared with representations in LTM directly, without having to retrieve the latter into the more central components of WM. Such a direct comparison or matching process is necessary for an efficient categorical identification of perceived objects and events: Everything we perceive is compared automatically to all representations in LTM, thus activating matching concepts as well as matching episodic representations. The same automatic comparison with LTM representations is also responsible for the generation of the familiarity signal discussed above in the context of recognition. This comparison returns a global similarity or match value that sums across all feature dimensions for which values are available for both the perceived stimulus and the LTM representation it is compared to. The relative weight of each dimension can be modulated by cumulative learning but not by *ad hoc* task demands or intentions. Thus, the outcome of a comparison in purely associative processing mode is a global similarity value based on a weighted average across all available feature dimensions.

In analytic processing mode, in contrast, comparisons use representations of the entities to be compared in the DA region. Entities bound to places in mental space are compared by assessing their distance separately for each dimension; how these distance values are used is determined by the current task set. Thus, in the analytic mode, entities can be compared with regard to specific feature dimensions, ignoring all other dimensions, and a small number of dimensional distances can be assessed separately and combined in any arbitrary way. For instance, we can compare Russia and India simultaneously on two dimensions, size of population and geographical size, and judge that India has a larger population but Russia has a larger land area. We can also integrate both sizes by a weighted-average rule to judge which country is "larger." Alternatively, we might compute a ratio of the two values to judge which country is more densely populated.

A special case of comparison is comparing relations. For instance, we can compare the relationship between mother and daughter to that between grandmother and mother, or compare the relationship between the planets and the sun to the relationship between the electrons and the nucleus in the atom. Such relational comparisons underlie the *relational mapping* step in analogical reasoning (Gentner, 1989). Relational comparisons require access to individual relations on separable dimensions, rather than a global judgment of similarity or associatedness. These relations must be made explicit by projecting them into the region of direct access—for instance, the relation between planets and sun can be represented as a mental model in space in which smaller objects revolve around a larger central object (Gentner & Stevens, 1983). Thus, whereas the first step in analogical reasoning, finding an analogue, involves retrieval from LTM, the second step, relational mapping, relies exclusively on the region of direct access and thus constitutes a prime example of analytical processing. Therefore, analogical-mapping tasks, in which participants fill in a missing piece in a given analogy (of the form: A::B=C::?), can be regarded as relatively pure measures of the capacity of the DA region. Tasks of this kind are found in many tests of fluid intelligence. The Raven matrices, one of the best single measures of fluid intelligence (Marshalek, Lohman, & Snow, 1983), can be understood as analogical-mapping tasks with three times three elements (A::B::C=D::E::F=G::H::?). Fluid intelligence, in turn, is closely related to measures of WM capacity (Kane, Hambrick, & Conway, 2005; Oberauer, Schulze, Wilhelm, & Süß, 2005). Together these facts support my assumption that measures of WM capacity essentially reflect the capacity of the DA region, which puts a limit on the complexity of structural representations that can be used in analytical reasoning.

The two modes of comparison—associative and analytical—map onto two corresponding modes of categorizing entities. Research on category learning has revealed two kinds of categorization tasks that are best solved by two distinct processing modes (Ashby & Maddox, 2005; Kloos & Sloutsky, 2008). Some categories are distinguished from each other by a single feature or a logical combination of very few features, and all other features of the entities to be categorized are irrelevant, and can vary widely within a category. Scientists and lawyers often strive to define concepts in this way—for instance, *iron* is defined by the number of protons and neutrons in its atoms, regardless of whether it appears in the shape of a nail or the hull of a ship. These categories are called *rule based* (Ashby & Maddox, 2005) because they can be described by relatively simple rules. Other categories are distinguished from each other on a large number of feature dimensions that combine in potentially complex, nonlinear ways (although linear combinations are easiest to learn, see Ashby & Maddox, 2005). The distinguishing features are often highly redundant, so that a random subset of them is sufficient for making highly accurate categorization decisions. These categories are called *information–integration* categories because categorization judgments are based on integrating feature information across many dimensions. Explicit categorization rules, if they can be formulated at all, are very complex because they must mention many features.

Kloos and Sloutsky (2008) capture essentially the same difference by their concept of *category density*: With dense categories, a large proportion of the features of exemplars are relevant for distinguishing members from nonmembers of the category, and the feature information is highly redundant, whereas with sparse categories, only one or a small subset of features is relevant, and all other features are uncorrelated with category membership. Therefore, learning of sparse categories is more dependent on selective attention to the relevant features. Kloos and Sloutsky show that sparse categories are best learned when the categorization rule is explicitly given, whereas dense categories are best learned when exemplars are presented. When given both kinds of information, adults learned rule-based representations of sparse categories, but similarity-based representations of dense categories. Children learned similarity-based representations for both kinds of categories, suggesting that forming similarity-based representations is the cognitively less demanding default approach to category learning. DeCaro, Thomas, and Beilock (2008) found that people with high WM capacity outperformed those with low capacity on learning low-dimensional rule-based categories, but performed worse than the low-capacity participants on learning higher dimensional information–integration categories.

Love (2002) provided evidence that higher dimensional categories, which are more difficult to learn than low-dimensional rule-based categories in a supervised learning regime, can be easier to learn in an unsupervised incidental learning regime.

Together these results support the distinction between two ways of learning categories, and two corresponding kinds of category representations. Dense categories can be represented as clusters in a high-dimensional feature space as provided by LTM. Their learning requires no selective attention to specific features, and new exemplars can be categorized on the basis of overall similarity (i.e., proximity to a cluster in the high-dimensional space). Sparse, rule-based categories can be represented as partitions in a low-dimensional mental space that includes only the relevant feature dimensions; the DA region provides a blackboard for defining that mental space. Exemplars are categorized by projecting their representations into that space, thus focusing exclusively on the relevant features. Learning of dense categories can occur incidentally, because all that is needed is the accumulation of exemplar memories in the high-dimensional feature space. Learning of sparse categories must rely on hypothesized (or given) rules that specify the relevant feature dimensions and the classification rule, and it requires engagement of the DA region of WM to represent the classification rule as a boundary in the space that is defined by the relevant feature dimensions. Therefore, learning of sparse, rule-based categories, but not of dense information-integration categories, depends on WM capacity.

4.3. Independent Selection of Declarative and Procedural Representations

I have argued above for separate sub-systems of declarative and procedural WM because I believe that this separation is an important feature for the functionality of the system. The separation preserves a high degree of independence between representations of objects and events on the one hand, and (cognitive) actions on the other hand.

Here I differentiate this claim, arguing that independence of declarative and procedural knowledge is a characteristic of the analytic subsystem. The DA region and the bridge are separate components, the contents of which are selected independently, and so are the focus of attention for declarative representations and the response focus for procedural representations. In activated LTM, however, I assume that declarative and procedural representations are more closely interwoven. Much evidence has been gathered showing that whenever a response is given to a stimulus, an association is built between the stimulus, the response, and the outcome, such that on the next occurrence of the same stimulus, the associated response and its outcome are primed (e.g., Hommel, 1998a; Rothermund, Wentura, & De Houwer, 2005). Learning such associations is functional because it enables the cognitive system to acquire the probabilistic contingencies between stimuli (or, more generally, situations), responses, and outcomes. A large part of our everyday actions are routines executed in common environments—we encounter the same or very similar situations again and again, and usually respond to them in the same way as many times before, expecting and typically obtaining the same outcomes. Being able to rely on learned associations between situations, actions, and outcomes in such cases bypasses the need to make new decisions at every juncture. At the same time, the system must avoid being enslaved by learned routines. Even after we have driven the same way from home to work thousands of times, we want to be able to deviate from the common route toward a new destination. Thus, the system must have the choice between following the learned routine and responding to a situation in a new way. This is essentially the choice between the associative and the analytic processing mode.

In the associative mode, the perceived stimulus or situation activates a matching representation in declarative LTM. This declarative representation is associated to one or several responses to various degrees, based on previous experience, and these responses are therefore activated accordingly. In associative mode, the threshold for retrieval from LTM into the bridge is lowered, and there is no strong competing stimulus–response binding in the bridge. Therefore, the response most highly activated through LTM associations is retrieved and selected by the response focus. In analytic mode, in contrast, the retrieval threshold is set high, shielding the bridge from the habits and routines in procedural LTM, and the desired task set is implemented by strong stimulus–response bindings in the bridge. The perceived stimulus or situation still activates a matching representation in declarative LTM, which activates responses that are associated to that representation, but the activation of responses in LTM has only a relatively minor priming effect. Response selection is controlled by the task set in the bridge, and this task set is selected on the basis of the currently dominant goal, independent of the stimulus.

To summarize, the present theory takes on many ideas from dual-process or dual-system theories of reasoning (e.g., Evans, 2003; Sloman, 1996) and of action selection (e.g., Kornblum, Hasbroucq, & Osman, 1990) and integrates them in a common framework. I think of the two modes of processing not as outcomes of two separate, independent systems of information processing, but as the endpoints of a continuum. This continuum reflects the relative weight of the analytic subsystem of WM (i.e., the region of direct access and the bridge, together with the focus of attention and the response focus) and the associative subsystem (i.e., activated LTM representations and their associations). The place on this continuum is regulated by two parameters, the threshold for retrieval from activated LTM, and the strength of bindings in the central components of WM. The retrieval threshold is set on a moment-to-moment basis by executive processes, and research on cognitive control is beginning to identify a number of variables that influence these executive processes, among them the amount of conflict between responses selected by the implemented task set and responses primed by associations (Botvinick, Braver, Barch, Carter, & Cohen, 2001), and the amount of performance pressure (Beilock & DeCaro, 2007). The second parameter, strength of bindings, is not under the control of executive processes but rather reflects the ability of the system to establish and maintain bindings and to minimize interference between them. This parameter therefore reflects a relatively stable characteristic of an individual's WM system, and it is the main source of individual differences in WM capacity and performance on tasks requiring analytical processing.

5. Concluding Remarks

Readers will have noticed that the ''working memory'' sketched here is not genuinely a memory. Rather, it is an attentional system that interacts equally with perception and with (long-term) memory. This can be illustrated with an example investigated by Halford and his colleagues, the comprehension of statistical interactions (Halford, Baker, McCredden, & Bain, 2004). The necessary information can be fully available for perception (e.g., in the form of a table or a bar chart) and yet people have severe difficulties grasping a three-way interaction and generally fail with a four-way interaction. A similar argument can be made with respect to many intelligence test tasks used to measure reasoning ability (Oberauer, Süß, Wilhelm, & Wittmann, 2003). The limiting factor for complex reasoning is not our ability to remember all the relevant pieces of information but to put them together by binding them into a common schema or a common cognitive coordinate system. This capacity for *relational integration* (Robin & Holyoak, 1995) applies equally to representations from memory and to representation of the perceived environment. My colleagues and I have developed tasks that measure WM capacity by testing people's ability to integrate given information into structures. The given information was either continually visible or had to be maintained in memory. Both task versions were highly correlated and were equally good predictors of reasoning ability (Oberauer, Süß, Wilhelm, & Wittmann, 2008).

WM has not evolved to serve us as a short-term store. The fact that it can also be used as such is better understood as a by-product of its ability to uphold a structural representation and shield it to some degree from unwanted, potentially interfering input from both perception and LTM. The main function of WM is to serve as a blackboard for information processing on which we can construct new representations with little interference from old memories, knowledge, and perceptual input, thus enabling us to investigate a hypothetical alternative state of reality, a future state—or some aspect of the past.

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CHAPTER THREE

When Emotion Intensifies Memory Interference

Mara Mather

Contents

Abstract

Many of our most vivid memories are of emotional events; in research studies, emotional events or items are often more likely to be remembered than neutral events or items. However, as pointed out in this chapter, the same characteristics that make emotional information memorable can also make it more subject to interference effects in memory. Thus: (1) being reminded of some emotional memories interferes with other memories evoking the same emotion; (2) it is more difficult to update one's memory of the context of emotional items than of neutral items; (3) it is harder to learn a new association to something that was previously associated with an emotional item; and (4) frequent reexposure to a cue to a negative memory increases forgetting of that negative memory.

1. Introduction

Funes not only remembered every leaf on every tree of every wood, but even every one of the times he had perceived or imagined it.
He told me: I have more memories in myself alone than all men have had since the world was a world. And again: My dreams are like your vigils. And again, toward dawn: My memory, sir, is like a garbage disposal.

From "Funes the Memorious" by Jorge Luis Borges.

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To have a perfect memory for every instant of one's life may seem desirable. Yet, as Borges illustrated in his story *Funes the Memorious*, a mind that is incapable of forgetting would also be one that fails to distinguish minutia from core knowledge; one that is incapable of abstract thought. Thus, a key feature of memory is what is forgotten, or not even learned in the first place. Although the most noticeable factor that leads to forgetting is the passage of time, researchers have found that forgetting is not just a passive process. Information competes for mental resources and so newly learned information is vulnerable to interference from other mental activity (for reviews see Anderson, 2003; Wixted, 2004).

Much research attests to the fact that emotional events or stimuli are less likely to be forgotten than neutral events or stimuli (for reviews see Kensinger, 2004; Mather, 2004; Reisberg & Heuer, 2004). This memorial advantage is due to a number of factors, including that emotional stimuli grab attention, that we tend to think and talk more about emotional events than neutral events, and that a brain region that responds to emotionally arousing stimuli (the amygdala) modulates memory consolidation activity in the hippocampus, a brain region that plays a key role in acquiring new memories.

Because of its dominance in attention and memory, it is not surprising that emotional information should be more likely to interfere with other information in memory than neutral information. This competitive advantage of emotional information has been demonstrated in many studies (for a review see Mather, 2007). However, some recent findings suggest that, in some cases, the emotional nature of a stimulus make it the *object* of more interference than it might otherwise face, leading it (or information linked to it) to be more likely to be forgotten than if the stimulus were neutral. Unlike Funes the Memorious's memory, normal memory processes are selective. This chapter will touch upon some of the interference or inhibition paradigms and findings that are relevant for emotional memory and review how emotional material may sometimes be more subject to interference.

2. Interference from Being Part of an Emotional Category

Having learned a list of related items (e.g., sleep, bed, rest, awake, tired, dream, wake, snooze, etc.), people are worse at recalling a particular half of the items from the list if they are shown a list of the other items on the memory test than a control group that is not shown any items from the list (Bäuml & Kuhbandner, 2003). Similar part-set cueing effects have been demonstrated many times under a variety of circumstances (e.g., Marsh, Dolan, Balota, & Roediger, 2004; Roediger, 1973; Rundus, 1973; Slamecka, 1968; Watkins, 1975). Findings of inhibition from part-set cueing are intriguing because they contrast with the idea that memory retrieval is facilitated by the activation of associated items, and many researchers have devoted effort to explaining the mechanisms of this ''persisting enigma in memory research'' (Nickerson, 1984).

Related to the part-set cueing effect is the finding that the repeated retrieval of a subset of items from a list can lead to forgetting of the nonretrieved items (Anderson, Bjork, & Bjork, 1994, 2000). In a typical retrieval practice experiment, participants learn lists of category–exemplar pairs (e.g., fruit–orange, drinks–scotch, fruit–banana). Then they are prompted to retrieve half of the exemplars from half of the categories with the aid of cued stem recall tests (e.g., fruit–or___). A retrieval-induced forgetting effect is demonstrated in the final cued recall test by reduced recall of unpracticed items from practiced categories relative to unpracticed items from unpracticed categories.

Both the part-set cueing effect and the retrieval-induced forgetting effect reveal that being part of a category can reduce a memory's chance of being recalled if other memories from that category have been retrieved more frequently or are activated first during a memory retrieval attempt. These category-based interference effects suggest that emotional memories may suffer from competition with memories that evoke similar emotions. For instance, reminding someone of a negative memory may make them less likely to retrieve as many other negative memories as if they had not been reminded of that memory.

To see this type of interference along emotional lines, a prerequisite is that emotions act as organizing principles in memory. Otherwise, activation of a memory that elicits a particular emotion would not activate other memories that also evoke that emotion, and there would be no need to resolve competition among emotionally similar memories. Relevant to this issue, some researchers have argued that that emotions activate associated information within an associative network/spreading activation model of memory (e.g., Bower, 1981; Ingram, 1984; Niedenthal, Halberstadt, & Innes-Ker, 1999) and there is evidence that emotional cues facilitate retrieval of memories with similar emotional qualities (e.g., Schulkind & Woldorf, 2005). These models and findings of memory activation along emotional lines suggest that there may also be memory interference along emotional lines.

Recent findings support this possibility of interference due to the emotional category of memories. One study examined retrieval-induced forgetting for autobiographical memories generated from cue words (Barnier, Hung, & Conway, 2004). Participants first generated memories in response to nine category cue words, of which three were negative (horrified, sickness, tragedy), three were neutral (hardworking, patient, polite), and three were positive (entertaining, excitement, happy). Participants were also asked to generate a unique personal cue word for each memory that would remind them of the memory. In a subsequent retrieval-practice phase, participants were asked to retrieve their previously generated memory in response to a category cue word/personal cue pair (e.g., hardworking–exams) three times. The experimenter gave them the cues to complete this retrieval for half of the memories generated for one negative, one neutral, and one positive category. On the final test, participants were shown all nine category cue words again and were asked to recall all the memories associated with each word. As would be expected from previous studies using category–exemplar word pairs such as fruit–orange, participants were more likely to later recall the memories that they had practiced retrieving than memories from unpracticed categories. In addition, they showed the standard retrieval-induced forgetting effect, as they were less likely to retrieve unpracticed memories from practiced categories than unpracticed memories from unpracticed categories. The novel finding was that retrieval-induced forgetting was greater for memories from emotional categories than for memories from neutral categories.

This finding of greater retrieval-induced forgetting for emotional memories suggests that the competition among memories from the same emotional category may require greater inhibition at retrieval than is necessary to resolve competition among memories from a neutral category. However, it is not clear whether the emotional nature of the memories was the key factor or whether the autobiographical memories generated in response to the different cue words differed on other dimensions.

Another experiment that showed that interference can occur based on emotional category membership used words with either positive or negative valence (Ferraro & King, 2004). In this study, participants received four trials, each consisting of a three-word triad of either positive or negative words. On each trial, they studied the words and then, after a distractor task, recalled them. For half of the participants, all four trials had words of the same valence. As expected, they showed proactive interference, with worse recall on each subsequent trial that had the same valence for the word triad. For the other participants, the words switched valence on the fourth trial. These participants showed a robust release from proactive interference, with recall that was numerically even higher than their first trial (see also Wickens & Clark, 1968). Thus, the proactive interference occurred along emotional lines, with interference seen only if the words were from the same emotional valence category as the words in the previous trials.

Interference based on membership in an emotional category was also seen in a paradigm in which participants learned a few critical lists (one list consisted of tools, another of diseases, and another of curse words) and many filler lists that were also categorized (Smith & Moynan, 2008). After the learning phase, participants either did unrelated tasks or a retrieval-biasing procedure in which they were repeatedly exposed to the filler lists but not the critical lists. Then they were asked to recall all the list names (e.g., tools) from the first learning phase. Participants showed a high level of forgetting for the critical list names, with 40% higher recall of the critical list names in the control condition. The rate of forgetting was similar for the emotional and nonemotional list names.

An important question is whether the interference effects in the studies reviewed above occurred along emotional lines only because the experimental structure highlighted the emotional nature of the memories, or whether memories from similar emotional categories would spontaneously interfere with each other, even if there were no external cues to use emotional categories. Sison and Mather (2007) used a modified part-set cueing design to examine whether the organization of information along emotional lines is an automatic process that always occurs in response to emotional stimuli or whether the categorical structures that lead to competition among same-category items vary depending upon the most salient organizational scheme at the time. Participants were shown a series of pictures. Each picture belonged to one of four categories: amusing animals, amusing people, fear-inducing animals, or fear-inducing people. Thus, each picture could be categorized based on whether it contained people or animals or whether it evoked amusement or fear.

After the initial slideshow presenting the pictures, participants in some conditions were cued to retrieve one picture at a time, all of which were from the same category (e.g., all the amusing people). They were shown a word describing the picture (e.g., "clowns") and asked to visualize the picture that matched the phrase and then to press a key when they had succeeded. After they pressed the key, the corresponding picture was shown. Ten minutes after this reminder phase, participants were asked to list as many of the pictures from the slide show as they could.

Unlike most part-set cueing or retrieval-induced forgetting paradigms, participants were not reminded of the categories on either the retrieval practice or the final memory test (they were not asked to recall the pictures separately by category and the categories were not used as retrieval cues). Instead, the only explicit statement that the pictures could be categorized was in the initial instructions. In the actor–salient condition, part of the instructions stated that participants would view pictures of animals or people, whereas in the emotion–salient condition, the instructions instead stated that participants would view pictures depicting amusement or fear.

As shown in Figure 1, Sison and Mather found a part-set cueing effect both for pictures from the same-actor category (e.g., fear-related people) and for pictures from the same-emotion category (e.g., amusing animals). The emotion effect reveals that pictures that elicit the same emotion as pictures that were recently reactivated are subject to interference, even if the topic of the picture is otherwise from another category (e.g., people vs animals). But a second key finding is that these impairments in memory for items from the same category depended on which category was mentioned

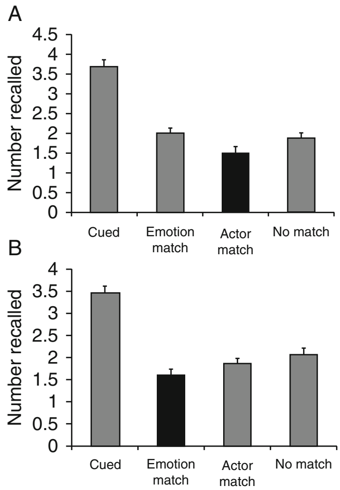

Figure 1 Sison and Mather (2007) found that: (A) when instructions mentioned people versus animal categories, recall of noncued actor-match pictures was impaired; whereas (B) when instructions mentioned amusing versus fear categories, recall of noncued emotion-match pictures was impaired. Thus, memory impairment for pictures from the same category as cued pictures only occurred if that particular category structure was made salient at the beginning of the experiment. Note: Figure adapted from data in Sison and Mather.

in the instructions. This suggests that which categories are most likely to influence memory competition are flexible, and the degree to which being from the same emotion category will lead to competition among memories will depend on whether the emotional similarity is salient.

Sison and Mather's findings suggest that the emotional nature of memories does not have a special status in determining which memories will interfere with each other, but can act like other categories (see also Smith & Moynan, 2008). Furthermore, the way that memories are categorized, and therefore the degree to which one memory will compete with another one during retrieval, is flexible and context dependent. This *ad hoc* nature of emotional categories is consistent with Barrett's (2006) proposal that the experience of emotion is itself an act of categorization that is based on prior experience and shaped by the current situation.

3. Proactive Interference for Emotional Items

Having learned an association between two things (such as that Emily lives in Portland) it is usually more difficult to learn a new, competing association (such as that Emily now lives in Seattle). Many studies have demonstrated this type of proactive interference using "AB–AC" paired-associate cued recall designs, in which participants first learn one set of cue-response pairings (AB) and then learn another set (AC). These participants do worse on a test for the AC pairs than other participants who are asked to learn entirely new associations in the second list (CD).

The ability to resolve proactive interference may contribute to many higher cognitive functions, especially working memory (Jonides & Nee, 2006). Prefrontal brain regions, in particular the left ventrolateral prefrontal cortex, play a role in resolving proactive interference (Nee, Jonides, & Berman, 2007). In addition, reliable individual differences in the ability to inhibit or suppress irrelevant information influence working memory capacity (Barrett, Tugade, & Engle, 2004; Conway & Engle, 1994).

In at least some models of proactive interference, the probability of recall is based on both the relative and the absolute strength of an item (e.g., Altmann & Gray, 2002; Mensink & Raaijmakers, 1988). This assumption leads to an interesting prediction regarding emotional associations, as recent evidence indicates that emotional items tend to yield stronger memory binding for their intrinsic features than neutral items do (Mather, 2007). Because of stronger proactive interference, people may have a harder time learning new associations with emotional items than new associations with neutral items.

Novak and Mather (2009) tested this possibility by having participants learn the association between pictures and their locations on the screen. In their first experiment, participants studied a series of 72 pictures, each shown in one of eight locations on the computer screen (none were shown in the center location). Half of the pictures were emotionally arousing (and negative) and half were more neutral. After the study phase, participants were shown each picture again in the middle of the screen and asked to indicate which location it had been shown in previously. They repeated this study–test cycle until they achieved perfect performance in two successive rounds. In the first round, there was no significant difference in picture–location memory accuracy (although location accuracy was slightly higher for the emotional pictures). However, after the first round, accuracy was significantly higher for the neutral pictures than for the arousing pictures. Further examination of the errors on the repeat rounds revealed that participants were more likely to repeat an initial location error again for arousing pictures than for neutral pictures (despite having seen the picture in the correct location again).

The finding that initial picture–location errors were more persistent for the arousing pictures suggested that, when associations change over time, participants might have more difficulty updating associations to arousing items than to neutral items. To test this, in the second experiment Novak and Mather changed the locations of half of the pictures on the fourth round of viewing the series of pictures. At the start of the study, participants were informed that some pictures might change locations in one of the rounds and that at the end of each viewing cycle they should report the most recent locations of the pictures. By the end of the third round, participants had learned the locations of most of the pictures. Among those pictures that they had correctly indicated its location on Round 3, participants were less likely to correctly indicate the changed locations of arousing pictures than neutral pictures on Round 4.

One surprising aspect of these data was that the difference between location memory for arousing and neutral pictures in Round 4 was not driven by a failure to notice the change in location. In fact, participants were slightly less likely to erroneously repeat the location from Round 3 for arousing pictures than for neutral pictures. Instead, their impaired performance for arousing pictures was driven by errors in which they responded with a different location than either the one the picture had been in for Rounds 1–3 (and that they had accurately recalled on Round 3) or the one it had been in for Round 4. This pattern suggests that participants noticed when arousing pictures changed locations—but they were less able to effectively bind the new locations to arousing pictures than they were for neutral pictures. This is an intriguing finding, as it argues against the possibility that the worse performance for new associations with emotional items is due to simple source errors in which people recall the initial association to the emotional item and assume it was the most recent association. Instead, participants seem to have more difficulty learning new associations to emotional items, even when they are aware that the original association is no longer current.

4. Impaired Associations to Emotional Harbingers

The role of memory strength in proactive interference leads to another interesting possibility with regards to emotional associations. Do people have a harder time learning new associations to cues that previously were associated with emotional items, because those emotional associations are more vividly recalled and are therefore more interfering than neutral associations? For instance, having learned to associate a particular phone ring sound with emotionally arousing phone calls, people might have a harder time remembering associated contextual details the next time the phone rings than if the phone were associated with neutral phone calls.

A series of experiments by Mather and Knight (2008) is consistent with this idea that learning associations with emotional items interferes more with learning subsequent associations than learning associations with neutral items. Mather and Knight examined how well people can learn new associations to cues that previously predicted emotional or neutral pictures. For instance, in their first experiment, Mather and Knight first asked participants to indicate as quickly as they could whether pictures shown on the computer screen were negative or neutral. Each picture was preceded by a neutral tone sequence (Figure 2A). Each tone sequence was played before multiple pictures, but always preceded pictures of the same type. Thus, some tones were emotional harbinger cues and others were neutral harbinger cues.

In the second phase of the experiment, participants were asked to learn the association between each of the tone sequences and a digit shown on the screen, with a color judgment task between trials (Figure 2B). Next, they were given a memory test for the tone–digit associations (Figure 2C). Participants were worse at remembering which digit had been associated with emotional harbinger tones than neutral harbinger tones. A follow-up experiment indicated that this impairment for emotional harbinger associations was also seen for tones that previously predicted positive arousing pictures. Thus, the emotional harbinger effect is consistent across arousing stimuli, regardless of valence.

In subsequent experiments, Mather and Knight replicated the emotional harbinger effect using visual harbinger cues (neutral faces) rather than the auditory tones. They investigated whether attentional narrowing could account for the findings. In other words, did the memory impairments

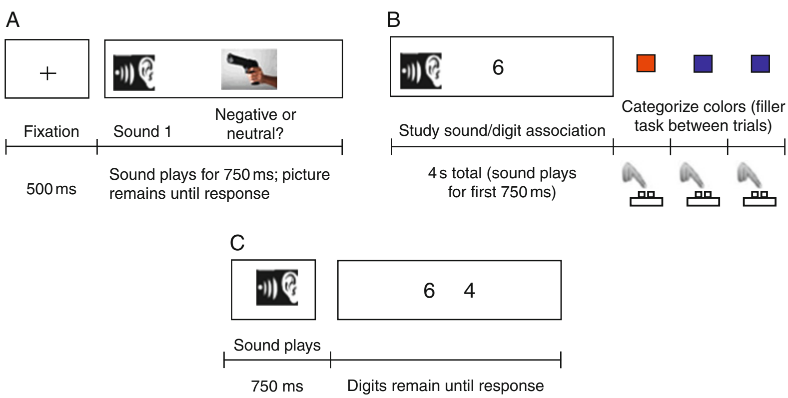

Figure 2 In Mather and Knight's (2008) Experiment 1, participants first learned which sounds preceded negative pictures (emotional harbinger sounds) and which sounds preceded neutral pictures (neutral harbinger sounds). Then, in the next phase, they were asked to learn associations between the sounds and digits (with an intervening color categorization task). In the final phase, they were asked to indicate which digit each sound had been paired with. Memory for the sound–digit pairings was worse for emotional harbinger sounds than for neutral harbinger sounds. Notes: Figure from Mather and Knight; pictures were in color.

occur because participants focused their attention onto cues that previously predicted something emotionally arousing, making it less likely they would learn other information presented at the same time? The findings indicated that memory narrowing could not account for the impaired memory for information associated with emotional harbingers. For instance, in Experiment 3, the new associations that participants were asked to learn to the neutral face harbinger cues were hats. The neutral face harbinger cue was shown either wearing the hat, or on the other side of the screen from the hat. In both conditions, participants were worse at learning which hat had been associated with neutral faces that had previously predicted emotional pictures than the hat–face association for faces that had previously predicted neutral pictures. Also arguing against an attentional narrowing hypotheses were findings from Experiment 4, in which memory was impaired not only for external associations with emotional harbingers (digits shown near the face cues) but also for intrinsic associations (the locations of the faces).

The finding that location memory was worse for faces that previously predicted emotionally arousing pictures than for faces that previously predicted neutral pictures contrasts with findings that location memory is better for pictures that are themselves emotionally arousing than for pictures that are more neutral (Mather, Gorlick, & Nesmith, 2009; Mather & Nesmith, 2008). Thus, in Experiment 5, Mather and Knight tested whether, in the same paradigm, participants would have impaired location memory for emotional harbingers compared with neutral harbingers but enhanced location memory for inherently emotional pictures compared with neutral pictures. Like in Experiments 3 and 4, in this experiment, participants started with a learning phase in which they saw a neutral face followed by a picture on each trial. They had to rate whether the picture was negative or neutral. Each neutral face appeared multiple times, always predicting the same type of picture. In the next phase, these neutral and emotional harbinger face cues were shown in different locations on the screen and participants were asked to learn the face–location pairings. Interspersed with these harbinger cue faces were new faces that were themselves either emotionally arousing (e.g., a woman with a black eye) or neutral (e.g., other participants saw the same woman without the black eye). Participants were then tested for their memory of all the face–location pairings (Figure 3).

There was a significant interaction, such that participants were worse at remembering the locations for emotional harbinger faces than for neutral harbinger faces, but better at remembering the locations for inherently emotional new faces than for neutral new faces. Furthermore, there was a significant main effect, with participants remembering the locations of the new faces better than the locations of the harbinger faces which had each been seen many times before during the cue learning phase (always in the center of the screen, in a location not used during the face–location association phase).

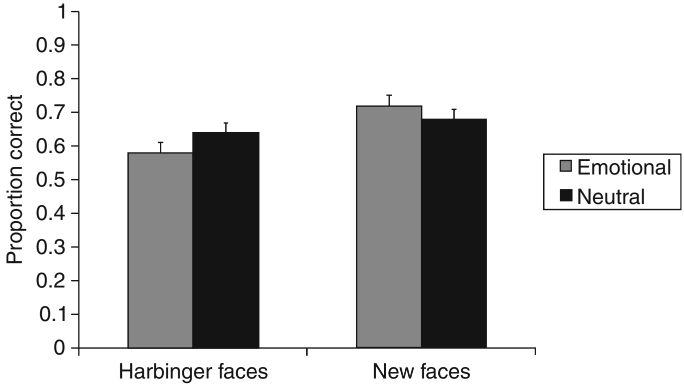

Figure 3 In Experiment 5 of their paper, Mather and Knight (2008) replicated the effect from their previous experiments that people were worse at learning new associations to emotional harbinger cues than to neutral harbinger cues (in this case, the cues were faces and the new associations were the face locations). In contrast, participants were better at learning the locations of new inherently arousing faces than new neutral faces. Thus, previous emotional associations to neutral faces interfered with learning new associations, whereas inherently emotional faces did not show the same interference. In addition, there was an overall impairment in learning the locations of the harbinger faces, suggesting that proactive interference from previous viewing of the faces made learning new associations to the faces more difficult. Note: Figure adapted from Mather and Knight.

These findings suggest that when a face is inherently arousing, people tend to have better location memory for it, as seen in our previous studies (Mather et al., 2009; Mather & Nesmith, 2008). However, when a face was previously associated with an emotionally arousing picture rather than a neutral picture, this previous emotional association makes it more difficult to learn a new and quite different association (the current location of the face). The main effect in which learning the locations of the harbinger faces was more difficult than learning the locations of the new faces suggests that proactive interference plays a role, even though the nature of the information being associated is different in the initial phase (faces with pictures) and the subsequent phase (faces with locations). Furthermore, this suggests that the reason that learning new associations to emotional harbingers is more difficult than learning new associations to neutral harbingers is because the initial emotional associations create more proactive interference than the initial neutral associations.

The emotional harbinger effect from Mather and Knight's (2008) study and the impaired emotional updating effect from Novak and Mather's (2009) study may reflect a general phenomenon, in which making an initial association that involves an emotionally arousing element makes it more difficult to learn new associations to any component of the original association. This would have important implications in everyday life, as it would mean that associations with emotional events are less likely to be updated or corrected when new information is available.

One interesting question is whether this emotional harbinger effect is related to the more general memory phenomenon in which additional study is more beneficial for previously studied items that have mostly been forgotten than for previously studied items that are remembered well at the time of relearning. For instance, increasing the spacing between two study sessions increases the retention of the material. In their new theory of disuse, Bjork and Bjork (1992) argue that the more accessible an item is at a given point, the less it will benefit from relearning opportunities (e.g., Storm, Bjork, & Bjork, 2008). Memories for emotional items will tend to be more accessible than memories for neutral items, and therefore relearning should be less effective for the emotional items. Particularly intriguing is the indication that relearning will not only be impaired for the item itself, but for associations with that item (Mather & Knight, 2008; Novak & Mather, 2009).

5. The Intentional Suppression of Emotional Memories

This chapter has already reviewed a number of ways in which emotional memories are more subject to forgetting and interference than neutral memories. However, one key factor not yet discussed is that emotional memories are more likely to evoke the desire to forget or remember than neutral memories. Unpleasant memories, such as the embarrassing thing one said during a meeting, can trigger a negative mood, just as pleasant memories can trigger a positive mood. Retrieving positive memories while avoiding reactivation of negative memories is one way to help regulate emotions (e.g., Rusting & DeHart, 2000; Sakaki, 2004). For instance, simply asking people to rate their emotions every page or so when they filled out a survey about their memories for their health and well-being years earlier made them remember their past in a more positive light and led them to be in a better mood after they completed the questionnaire than when they started, unlike the control participants who were not asked to rate their emotions (Kennedy, Mather, & Carstensen, 2004). Likewise, asking people to think about how they feel about choices just after they make them can lead them to show more of a choice-supportive bias later when they recall the attributes of the choice options, attributing more positive features to their chosen option and more negative features to the rejected option (Mather & Johnson, 2000). In general, people are more likely to remember positive autobiographical events than negative ones, and negative feelings associated with events fade faster than positive feelings (Walker, Skowronski, & Thompson, 2003). Coping mechanisms that minimize the impact of negative events seem to contribute to the advantage for pleasant memories (Taylor, 1991).

The notion that the desire to forget an unpleasant memory could somehow contribute to it being forgotten goes back to Freud's concept of repression, in which mental processes "strive towards gaining pleasure; psychical activity draws back from any event which might arouse unpleasure" (Freud, 2003, p. 68). Despite its extensive history, the concept of memory repression is still controversial (Brewin, 2007; Erdelyi, 2006 and associated commentaries). Some psychologists believe that amnesia for traumatic events is not uncommon (Arrigo & Pezdek, 1997; Gleaves, Smith, Butler, & Spiegel, 2004) whereas others are skeptical that emotionally charged memories tend to be repressed (Schacter, 2001) or that anything beyond normal forgetting mechanisms are needed to account for forgotten episodes of trauma (Kihlstrom, McNally, Loftus, & Pope, 2005).

One reason that experimental psychologists have been skeptical of the notion of repression is that it has been difficult to demonstrate repression in controlled laboratory studies. Recently, however, Anderson and Green (2001) provided an experimental task that they argued demonstrated repression. In their study, participants first learned to say an associated word whenever they saw its cue word (e.g., see "ordeal," say "roach"). In the subsequent "think/no-think" phase, they saw some of the cue words printed in green and some in red and were asked to respond with the associate for the green cues but to not respond to the red cues. Furthermore, for the red cues, participants were asked not to even let the associated word come to mind—they were supposed to avoid thinking about it. The more frequently participants saw a cue word in red during this phase, the less likely they were to recall it later when shown the cue word or a word stem completion such as "insect–r____." This procedure may serve as an analog to real-life situations in which people encounter something or someone associated with an unpleasant memory but use cognitive control mechanisms to avoid thinking about the associated memory.

Several studies followed up these findings using emotional stimuli, to see if people are more or less likely to suppress emotional associates than neutral associates. One study found that when repeatedly shown faces and asked either to think or not to think of a word or picture previously associated with each face, participants showed larger facilitation and inhibition of associated items that were negative than of items that were neutral (Depue, Banich, & Curran, 2006). However, another study using word pairs with neutral cues and emotional response words found that facilitation and inhibition were less effective for unpleasant words than for pleasant words (Marx, Marshall, & Castro, 2008), whereas other studies have found no differences in the effects of trying not to think about positive and negative stimuli for nondepressed participants (Hertel & Gerstle, 2003; Joormann, Hertel, Brozovich, & Gotlib, 2005). Thus, although these studies do not yield clear conclusions about whether it is easier or harder to suppress positive, negative, or neutral associations, they suggest that trying not to think of emotional associations has similar effects as trying not to think of neutral associations, leading people to be more likely to forget them later.

This ability to intentionally forget emotional stimuli has also been demonstrated using directed forgetting paradigms, in which participants are presented with two lists of words and instructed to forget one of the lists but remember the other one (Myers & Derakshan, 2004; Power, Dalgleish, Claudio, Tata, & Kentish, 2000; Wessel & Merckelbach, 2006). At least among nondepressed college students, telling them to forget a list of negative words is just as effective as telling them to forget a list of neutral words; in both cases, they are more likely to forget those words than control participants not given the forget instructions, with very similar forgetting rates for negative and neutral words (Wessel & Merckelbach).

Although the studies reviewed above reveal that telling people not to think about an emotional item or set of items decreases the likelihood they will recall that item or set later, none of them attempt to measure what people do without explicit instructions. To examine whether people spontaneously try to suppress negative memories more than positive or neutral memories, Mather and Mangold (2008) designed a procedure with a similar structure to Anderson and Green's (2001) think/no-think procedure, but without any explicit instructions to think or not think about associations to the cues. In the first phase of the study, participants were asked to learn the association between faces and pictures. They learned the face–picture associations in lists of nine items. All of the faces were neutral, and the pictures were either neutral, positive or negative. After being shown each face–picture pair once, participants were shown each face and asked to recall the associated picture. After they gave an answer, they were shown the actual associated picture and then another face in the list. They repeated the test for the nine pairs until they remembered all of the pictures correctly. In this fashion, participants learned four lists of face–picture pairs.

The next phase of the study was designed to simulate the undirected nature of everyday reexposures to memory cues. Participants saw some of the faces again, but were not instructed about whether or not to think about the associated pictures. Instead, they were shown each face on the screen for a few seconds, then the face disappeared, replaced by a question about it (e.g., "Would you like to go out for a drink with the person in the picture?"). Thus, participants were free to reactivate their memories of the associated picture while they looked at a face cue, or to avoid thinking about the association. During this reexposure phase, one third of the faces were shown once, one third were shown six times (each time followed by a different randomly selected question), and one third were not shown.

Next, participants were shown each face from the original face–picture association-learning phase and asked to recall which picture it had been associated with. Since some of the faces had been seen during the reexposure phase and some had not, this test provided a measure of how seeing the face again affected memory for what it had originally been associated with. In general, participants were less likely to recall pictures associated with faces shown six times in the reexposure phase than pictures associated with faces shown only once or not at all. Thus, frequent reexposure to faces interfered with memory for previous associations to the faces. Presumably, reexposure impaired memory for previous associations at least in part because of retroactive interference from new associations to the questions.

However, the main effect of reexposure was qualified by a significant interaction of picture valence, number of reexposures, and participant gender. Males recalled fewer associated negative pictures with repeated reexposure to the face cues but did not show this decrease in memory for neutral pictures. In contrast, females did not show this selective diminishment of negative associations with repeated reexposure to the face cues.

Another question of interest in this study was whether depression status would predict the degree to which people spontaneously suppress negative memories. Previous studies have examined how effectively depressed participants forget associated items or whole lists when asked to do so (Hertel & Gerstle, 2003; Hertel & Mahan, 2008; Joormann et al., 2005; Power et al., 2000). Depressed participants sometimes show impairments in the ability to suppress information when asked to (Hertel & Gerstle; Power et al.). However, these studies did not examine spontaneous engagement in suppression or enhancement of memories.

Categorizing participants by whether they were above or below the average score on a depression scale in Mather and Mangold's study revealed that females with above average depression scores had better memory for the negative associations to repeatedly reexposed face cues than did females with below average depression scores or males with above average scores. Thus, females experiencing higher levels of depressed mood were less likely than other participants to successfully suppress negative associations with repeated reexposure to reminders of those negative memories.

These individual differences based on participant sex and depression levels are consistent with research showing that, in response to a sad or depressed mood, women are about as likely to ruminate about their feelings as they are to try to distract themselves, whereas men are more likely to try to distract themselves from the negative mood (Nolen-Hoeksema, Morrow, & Fredrickson, 1993). Females' greater tendency to ruminate rather than distracting themselves in response to feeling down about something seems to be one reason that women experience more depression than men do (Nolen-Hoeksema & Jackson, 2001; Treynor, Gonzalez, & Nolen-Hoeksema, 2003). The results from Mather and

Mangold's study suggest that sex differences in the likelihood of spontaneously suppressing negative associations to cues may contribute to females' greater risk for depression.

6. Concluding Remarks

Inhibition is a key component of a functioning memory system. In this chapter, I reviewed findings that demonstrate that the emotional response that some information evokes can make it more subject to interference. This emotion-based susceptibility to interference can happen for a variety of reasons.

First, emotional responses to information can serve as an organizational principle in memory, leading items that evoke similar responses to be categorized together. Most memories have the potential of being categorized in multiple ways. For instance, memory for a picture of clowns could be categorized as something involving people, something amusing, or something seen during the experiment session. Many previous studies have demonstrated that when some members of a category are retrieved, nonretrieved members of the category are less likely to be recalled later than if no category members had been retrieved (for a review see Nickerson, 1984). Like these other types of categories in memory, emotional categories create interference (Barnier et al., 2004; Sison & Mather, 2007; Smith & Moynan, 2008). However, being part of both a semantic and an emotional category does not automatically increase the amount of interference a memory is subject to. Instead, interference happens along emotional or semantic lines depending on which type of categorization scheme is most salient to the rememberer (Sison & Mather).

Second, I reviewed findings that suggest that emotion can increase proactive interference. Novak and Mather found that it was harder for participants to learn a new location of a picture previously seen in another location if that picture was emotional than if it was neutral. Thus, memory binding that helps create associations among features of an object is more resistant to updating for emotional objects than for nonemotional objects. Furthermore, findings from Mather and Knight's (2008) series of experiments suggest that this impaired memory updating for emotional associations is a surprisingly general phenomenon that extends to neutral items that were previously associated with emotional items (emotional harbingers) and leads to impaired new learning of associations that have no overlap or similarity to the original memory representation. For instance, participants were worse at learning which digit was associated with emotional harbinger sounds (sounds that previously preceded emotional pictures) than with neutral harbinger sounds (sounds that previously preceded neutral pictures) even though no numbers had been included in the original learning phase. This intriguing set of findings suggests that people will be less likely to learn any type of new association to something once it has been associated with something emotional.

Cognitive aspects of emotional memories, such as being associated with other similar memories and stronger initial memory representations, are not the only factors relevant for memory interference. Emotional memories are more likely to tap into people's hopes, desires, and fears. To maintain positive moods or curtail negative moods, people should aim to remember happy events and forget disturbing ones. Thus, people may be more likely to try to suppress emotionally negative memories than neutral or positive ones. Findings described in this chapter suggest that there are individual differences in how likely people are to spontaneously suppress negative associations (Mather & Mangold, 2008). Repeated exposure to faces previously associated with negative pictures impaired males' ability to remember the original face–picture associations more than it impaired females' ability to remember the original associations. Furthermore, females with above-average scores on a depression scale were the least likely to show selective forgetting of the negative associations. This pattern fits with previous research indicating that females are less effective at suppressing intrusive negative thoughts (Nolen-Hoeksema, Wisco, & Lyubomirsky, 2008). It also provides an example of how, because of their evocative content, negative memories may be more likely to be the target of memory suppression attempts. One important question for future research is whether depressed females are less likely to try to suppress negative associations or whether they are as likely to try to do so, but are less effective at it. Research with older adults indicates that they use cognitive resources to enhance processing of positive information but to diminish it for negative information—but that when fewer cognitive resources are available, they can no longer selectively favor positive over negative information (Knight et al., 2007; Mather & Knight, 2005). Similarly, depressed females may desire to avoid dwelling on negative memories, but to be ineffective at doing so because of cognitive control deficits associated with depression (e.g., Hertel, 2000, 2007).

Emotional events have a special status in memory. They attract greater attention that enhances initial perceptual binding of various features (Mather, 2007). Emotional memories tend to be more long lasting both because they elicit more memory rehearsal and retellings and because emotional events evoke amygdala activity that enhances hippocampal consolidation processes (Canli, Zhao, Brewer, Gabrieli, & Cahill, 2000; McGaugh, 2000). However, as outlined in this chapter, some of the very same reasons that emotional events are more memorable can lead them to be more subject to memory interference or suppression.

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CHAPTER FOUR

Mathematical Cognition and the Problem Size Effect

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Contents

Abstract

We review a foundational finding in the area of mathematical cognition, the problem size effect, as it has been studied and modeled across the past 30 years. Early research on the effect indicated a substantial role for memory retrieval, as opposed to simple counting-based performance, leading to research on the nature of the memory representation supporting such retrieval, the emergence of memory retrieval in development, and the underlying source of the problem size effect. Three possible reasons for the problem size effect, one based on strength in memory, one on errors, and one on strategy-based

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responding, are considered, along with the role of working memory and the individual difference variable of math anxiety. A unifying theoretical framework is suggested, based on strength, that yields both error and strategy predictions that entail working memory effects. We conclude with remarks concerning the likelihood that the problem size effect is changing, probably due to educational factors, with clear consequences for both theories and for mathematical achievement.

1. Introduction

This chapter is a selective overview of the area of research known as mathematical cognition, the study of cognitive processing in the domain of number and mathematics. That is, we are interested in the mental processes and structures involved in reasoning and thinking about numbers and math, and about solving arithmetic and math problems. The focus is especially on the problem size effect, a benchmark empirical effect in the area, because of its centrality to theoretical accounts of cognitive processes in arithmetic, and because of the leverage it provides when we consider other aspects of processing, for example, the role of working memory in math processing. Furthermore, the review is ''cognitive'' in that it considers research done within the mainstream cognitive science approach, that is, research examining cognitive processes and structures inferred from response latencies, error rates, verbal reports, and, increasingly, event-related potential (ERP) and image-based scanning techniques. In contrast, a chapter with an educational focus might seek answers to the same questions—for example, ''how do people perform arithmetic?''—by investigating school curricula or teaching methods, by focusing on normal versus developmentally delayed math learners, and by measuring outcomes like math achievement scores on standardized tests.

This overview begins with the 1970s, essentially when information processing models of performance were first brought to bear on the topic of performance to number and arithmetic tasks. The review continues up through current research efforts, and ties in two related topics, an examination of the role of working memory in the performance of arithmetic and math, and the effects of math anxiety on performance. Developmental research results have appeared at significant junctures throughout the history of the field and therefore are covered in this chapter as well. This is not surprising given the important role of schooling in arithmetic and math, first, and second the importance the developmental findings have often played in theory development. Nonetheless, the primary focus of the chapter remains on theoretical accounts of mature cognitive representations and processes involved in number and math.

2. Early Research

2.1. Early Groen and Parkman work

Two papers by Groen and Parkman, a short report on adults' performance (Parkman & Groen, 1971) and a *Psychological Review* article (Groen & Parkman, 1972), provided the first chronometric studies of performance to simple addition problems in the literature. First graders were shown simple addition problems in the form $m + n = \_\_$, and had to press one of 10 buttons marked with the numbers 0–9 to indicate the correct response; the largest problem tested was 5 + 4. Adults were shown problems in the form $m + n = k$, where k was the correct answer on half of the trials; on the other half of the trials, when k was incorrect, it differed from correct by no more than ± 2. Adults saw all 100 of the "basic addition facts," problems with operands m and n ranging from 0 to 9. Groen and Parkman's analysis of their first graders' data revealed a linearly increasing reaction time (RT) function across problems. To further determine the nature of the process accounting for the increasing slope, they considered five different counting models, embedded in an information processing model inspired by the additive factors logic popularized by Sternberg (1969) at that time. In all cases, they assumed that a mental counter was set to some value and was then incremented by ones until some final value was reached, at which point the final value was read out as the answer to the problem. The slope of the regression line, obtained from the empirical data, was taken as an estimate of the time needed to increment the counter. The particular variable used as the incrementing value was, of course, taken as indicative of the nature of the underlying counting process.

Given a problem $m + n = \_$ (e.g., 3 + 2 = ?), the five models tested five possible variables that could account for incrementing: the Sum, First Addend, Second Addend, Maximum Addend, and Minimum Addend. So for example, in the Sum model, the counter would initially be set to 0 and would then be incremented m times then n times, for a total of k, the sum. Similarly, in the First Addend model, the counter would always be set to the first addend m in the problem (here 3), then incremented by the second addend n (here 2), such that n should be the best predictor variable in the regression analyses.

In fact, regression analysis indicated that the best fitting model for first graders was provided by the Minimum Addend (R^2 was 0.76). Thus, Groen and Parkman concluded that first graders performed simple addition by *min* counting, a process known in educational settings as "counting on"; set the counter to the larger of the two values, then count on by ones for the value of the smaller number, the *min*, as in 3, 4, 5 for the problem 3 + 2. In their analysis, the slope of the regression line was 410 ms, suggesting that first graders' mental counting rate was roughly 400 ms per increment.

The only noticeable departure from this linear function for first graders was performance to tie problems, for example, 2 + 2, 3 + 3, which showed considerably faster than predicted performance, and in fact no systematic increase in RT at all. Groen and Parkman (1972) suggested that "it is convenient to assume that they are faster then (sic) they should be because the subject has memorized the correct response" (p. 335), a process later described for adults as one of "direct access" to a stored memory representation.

The same analyses were conducted on adults' responses to true equations, and yielded results that were similar in many respects. In particular, the best fitting equation was once again the minimum addend function. Further, false trials were about 75 ms slower than true trials, but both functions had nearly identical slopes. This suggested, according to additive factors logic, that the stage responsible for making the yes/no decision was separate from the stage responsible for the increasing RT across *min*; that is, the decision stage was separate from the stage responsible for computing the sum of the problem and came after the computation stage.

Groen and Parkman noted that there were two obstacles preventing them from clearly advocating the *min* model as an explanation for adults' performance. First, although the *min* model had the highest R^2 value in the analyses (0.73), the sum of the problem was nearly as significant a predictor of RT as the minimum addend (R^2 = 0.71); in other words, there was no statistical reason to prefer the *min* over the sum. More seriously, the slope obtained for the minimum addend variable in the adults' analysis was a mere 20 ms. Groen and Parkman pointed out that it was highly implausible that this could be a reasonable incrementing rate for adults' mental counting, "since the rate of silent counting in adults is at best one number every 150 milliseconds" (p. 340).

Instead, they proposed a "direct access plus counting" model, in which the obtained slope of 20 ms was an artifact of averaging two kinds of trials, direct access trials with a slope of 0, and trials on which direct access failed and were consequently performed via the "childish" *min* counting process, with a slope of 400 ms. On this set of assumptions, direct access would be expected to account for 95% of the trials, with 5% accomplished by slow *min* counting. By averaging together 95% of trials with a zero slope and 5% with a 400 ms slope, one would observe an overall slope of 20 ms per increment.

Counting-based explanations of arithmetic performance appealed to Groen and Parkman, and apparently to many other researchers, for a fairly straightforward reason—they were tractable within a computation-based, that is, computer-based framework. That is, a simple computer-inspired, flow-chart model, such as the counting model proposed by Groen and Parkman, seemed to provide a parsimonious and explicit model of how number-based processing could proceed. Numbers, after all, could be counted, could be implemented in computer-based architectures of the day and did not need assumptions about the nature of memory representations or other processes for them to work; set a counter, increment the counter, then read out the updated value to a response mechanism (Groen & Parkman, 1972, Figure 1). It was clear, especially as Groen and Parkman discussed alternatives to their *min* counting model, that they were averse to premature theorizing about memory representations, saying they had not considered reproductive models largely because such models would have introduced "an excessive number of arbitrary assumptions" (p. 342).

The clear speed advantage of tie problems, however, and the unreasonable estimate of 20 ms as an incrementing rate for the mental counter, did prompt Groen and Parkman to propose direct access as a memory-based mechanism to supplement counting. This approach, although relying on memory, essentially relegated the memory function to a null role—it contributed no time to the overall RT of a trial (or contributed only a constant amount of time), it operated in an immediate, direct access fashion, presumably in much the same way as direct access functioned in accessing a memory location in a computer. No further explanation of the direct access process was provided, except to say that answers had been "memorized," and to assert that the retrieval process failed upon occasion, thus triggering the reconstructive, counting-based solution seen in first graders.

2.2. Fundamental Questions

While retrieval failure is certainly a plausible construct, both in memory for math and any other long-term memory situation, our initial work on mental arithmetic (Ashcraft & Battaglia, 1978; Ashcraft & Stazyk, 1981) questioned three aspects of Groen and Parkman's explanations; the adherence to counting-based explanations, the possibility of direct access, and the notion of a separate decision stage following computation. We take these issues in turn.

2.2.1. Counting

The first question involved counting, and the aversion to theorizing about memory representations. Purely on intuitive grounds, and based on general principles of incidental learning, it seemed implausible that adults persisted in counting when asked to solve $3 + 2$ or $6 + 7$. Simple addition is almost universally taught in first grade, after all, suggesting that continued reliance on counting on the part of college students was unlikely. Furthermore, the generality of counting-based explanations seemed dubious to us, especially "in view of other cognitive arithmetic operations, such as multiplication or division, for which a counting-based model provides an extremely cumbersome explanation" (Ashcraft & Battaglia, 1978, p. 528). Note, for example, that counting-based explanations of multiplication asserted that adults counted by one of the problem's multipliers, for example, for 7×4, one would count by either 7s or 4s, as in "7, 14, 21, 28" (e.g., Parkman, 1972). Several researchers noted the theoretical inconsistency of this suggestion, that adults were limited to counting by ones in addition, but could count by any unit size in multiplication (e.g., Miller, Perlmutter, & Keating, 1984; Stazyk, Ashcraft, & Hamann, 1982).

2.2.2. Direct Access

Our view on the notion of direct access was colored by a somewhat different *Zeitgeist* than the computation-based inspiration that motivated Groen and Parkman. At the same time as Groen and Parkman's early work on cognitive arithmetic, research was advancing in areas like semantic memory and word recognition (e.g., Collins & Quillian, 1972; Meyer & Schvaneveldt, 1971), research that depended heavily on differences in retrieval times to formulate theories about how concepts were represented in memory. To take a (then) commonly used example, differences in RT between "A robin is a bird" and "A robin is an animal" (e.g., Collins & Quillian, 1969) were being interpreted as indicating how distant concepts were from one another in a hypothesized memory representation, or how rapidly or slowly concepts could be activated during memory search. Such thinking inspired some of my own early research in the area of semantic memory (e.g., Ashcraft, 1976). Given this background, it was difficult to accept Groen and Parkman's (1972) notion that there would be no differences in retrieval time among the addition facts, the zero slope across increasing problem size they predicted under direct access. Tie problems indeed showed a seemingly flat RT profile across problem size (e.g., Groen & Parkman, Figure 4), but extrapolating that to all problems under direct access seemed unjustified.

2.2.3. Sequential Stages

Finally, we noted that in the Groen and Parkman experiment with adults, all false problems had been shown with incorrect answers that deviated from the correct answer by no more than ± 2. In other words, the degree to which problems were incorrect was held constant, and this seemed to us the likely reason that there had been merely a constant RT difference between true and false problem sets in the results. A more thorough test seemed in order, especially since the result was being used in an argument based on additive factors logic to support the existence of a separate decision stage that operated after the calculation stage.

To summarize, we questioned the assumptions of counting and direct access as explanations of adults' simple arithmetic processing, and questioned the support for a model of performance that relied on sequential, independent stages of processing.

2.3. Initial Studies in the Ashcraft Lab

In our first studies (Ashcraft & Battaglia, 1978; Ashcraft & Stazyk, 1981), we tested the 100 basic facts of addition, the single digit operand facts $0 + 0$ up through $9 + 9$, again using the true/false verification task (Experiment 2 in Ashcraft & Stazyk also tested sums up to 30). We departed from the Groen and Parkman (1972) procedures, however, by manipulating the "split," the degree to which incorrect answers differed from the correct value. In Ashcraft and Battaglia, half of the incorrect answers differed by ± 1 or 2, and half by ± 5 or 6, and in Ashcraft and Stazyk, splits were ± 1, 5, 9, and 13. Conventional and regression analyses were conducted on both RTs and errors.

2.3.1. Counting

Our results spoke convincingly against Groen and Parkman's (1972) conclusion that adults rely on counting when performing simple addition, whether *min* counting or any other simple counting process. In particular, a scatterplot and regression analysis of the RTs revealed an exponentially increasing pattern across the sum of the problems; technically, the best fitting regression equation used sum^2 as the predictor variable, when tie problems were excluded from the analysis (ties had also been excluded from Groen and Parkman's *min* analysis results, of course). The conclusion was not that some special significance attached to the squared power of sum, as opposed to some other power. Instead, the point was that no simple counting-based model could account for a nonlinear increase in RT. The sum^2 result replicated in a second experiment, reinforcing the conclusion that counting could be rejected as the basis for adults' performance to simple addition problems. Instead, we proposed that adults were searching through a memory representation for the sums of the problems. Because of the longer RTs for large problems, it seemed clear that the search through memory was somehow lengthier or more difficult for those answers.

2.3.2. Direct Access

Ashcraft and Stazyk (1981) conducted several detailed tests of their RT data in conjunction with Groen and Parkman's (1972) predictions about direct access, and in particular their predictions about the proportion of trials on which direct access would fail, thus necessitating the backup counting process. We modeled the analyses first on the presumed incrementing rate of 20 ms per increment from Groen and Parkman's data, and then on our own obtained rate when minimum addend was forced as the regression predictor variable, 73 ms. For the Groen and Parkman value, one would expect direct access on 95% of the trials, and a 5% retrieval failure rate. For the slope value derived from our data, direct access should have accounted for 82% of trials, with retrieval failure occurring 18% of the time.

We examined the fastest 95% of trials, and the fastest 82% of trials, under the prediction that these should exhibit a zero slope across either minimum addend or sum of the problem (or *sum*^{2}). Instead, we found these faster problems still exhibited a significant problem size effect, in contradiction to the Groen and Parkman prediction. Indeed, we had to assume a retrieval failure rate of 50% before the RT patterns became nonsignificant, a rate we judged to be "a strikingly unreasonable value to accept in order to support the notion of direct-access retrieval" (p. 190). Thus, we made parallel claims to those advanced in the semantic memory and word recognition literatures; we claimed that retrieval of addition problems was a process that consumed time, and that this time increased as the sum of the problem increased. In fact, in the Ashcraft and Stazyk (1981) paper, we used (apparently for the first time) the term "problem size effect," claiming the general principle that response time and error rates increase as the size of the problem increases, where "size" here was defined as the sum of the addition problem.

2.3.3. Sequence of Stages

Banks (1978) and others (e.g., Moyer & Landauer, 1967) had conducted extensive work on number comparisons, demonstrating clearly what is known as the symbolic distance effect; judgments of which of two numbers is larger/smaller are facilitated when the numerical distance between the numbers is greater. Given this, it was perhaps not surprising that our manipulation of split in the Ashcraft and Battaglia experiments revealed a significant decision stage effect—problems with an answer that deviated more from the correct value were faster to reject than those with answers that deviated less. Although the problems with splits of ± 5 or 6 were still somewhat slower than the corresponding true problems, they were significantly faster than those that differed only by ± 1 or 2. We introduced a more pronounced manipulation of split in the Ashcraft and Stazyk (1981) paper, with splits up to ± 13; for example, $7 + 9 = 3$ or $7 + 9 = 29$. For such problems, that is, larger addition facts, this extreme level of split led to faster RTs than was found for the corresponding true problems, faster by about 200 ms.

This finding, in retrospect, was more challenging to sequential information processing models than we realized at the time. We certainly interpreted the effect as suggestive of a decision or evaluation process that operated in parallel with ongoing retrieval (e.g., Ashcraft, 1982), and used terms such as "a short-circuiting" of the retrieval process based on magnitude estimations (Ashcraft & Battaglia, 1978). But this aspect of the results was of less concern to the community of mathematical cognition researchers than other aspects at that time, and the larger field of cognition was only slowly coming to the realization of how parallel processing undercut the utility of Sternberg-inspired information processing models. Interestingly, the split effect continues to be a focus of investigation currently, as discussed later, because of the insights it provides on the issue of exact versus approximate computations.

3. Three Salient Questions

This early work from our lab raised three salient questions. First, to our satisfaction, we had established the principle that adults rely heavily on memory, rather than counting, when they perform simple addition—saying this now, some 30 years later, when it is a commonly accepted conclusion, sounds unremarkable, but at the time it was new. But the question remained—if adults were relying on memory, then what was the nature of their memory representation, how was it organized? Second, given that it was rather firmly established that young children relied on counting in their early addition performance, when did they begin to switch from counting to memory-based performance? Was that switch related to other math learning taking place concurrently, say the introduction of multiplication during later elementary school years? And third, what was the underlying explanation for the problem size effect? Why did adults continue to demonstrate this effect, even after years of practice with the simple facts? Did it characterize all arithmetic operations? All ages of participants?

3.1. The Nature of the Memory Representation—Networks

Our initial theoretical efforts to explain the memory results we obtained were guided by the same assumptions as those behind work in semantic memory (e.g., Collins & Quillian, 1972), the notions of an interrelated network of information accessed by means of spreading activation. We hypothesized that arithmetic knowledge was stored in a network representation, was accessed by a spreading activation process in that network, and that related information would be primed during the process of retrieval. Such a representation might account for the exponential increase in RT we had observed in addition, we thought, if larger problems were in some metaphorical sense more "distant" from the origin of the search point, or more difficult to retrieve. We considered this analogous to slower or more difficult retrieval for a less dominant member of a category (Rosch, 1973) or a less dominant property of a semantic concept (Ashcraft, 1976).

A report by Winkelman and Schmidt (1974) came to light that provided encouragement along those lines, a report in which "confusion" problems like $3 + 4 = 12$ or $5 \times 3 = 8$ had been shown to generate particularly slow RTs and high error rates. The implication was that addition and multiplication were interrelated in a memory representation, with answers in one operation accessed and easily confused with answers in the other operation. We elected to avoid confusions from one arithmetic operation to another, on the chance that the Winkelman and Schmidt result depended on misperception of the operator sign (addition and multiplication problems had been presented in mixed blocks). Instead, in Stazyk et al. (1982, Experiment 3), we presented pure blocks of simple multiplication problems, half true and half false. False answers were either unrelated to the problems' operands, as in $4 \times 7 = 25$, or were multiplicatively related to one of the operands, as in $4 \times 7 = 24$ or 35. We expected to see evidence of confusions within the multiplication operation, that is, evidence that answers within a multiplication fact "family" were interrelated. Specifically, this was a prediction of a priming effect, in that multiplicatively related lure answers were predicted to be slower to reject than those that were unrelated.

A second manipulation was also included as a further test of the network and activation ideas, another manipulation of priming. The problem's operands were presented either 200 or 600 ms in advance of the answer, that is with a stimulus onset asynchrony (SOA) of 200 ms versus 600 ms. We reasoned that if problems and their answers are stored in an interrelated network, and if that network is activated during retrieval, then there should be evidence of that activation even at a short SOA, indicative of an automatic spread of activation.

In brief, these predictions were both upheld. There was significant slowing of the response times to table-related lure answers, in other words a significant confusion effect. Multiplicatively related answers were indeed effective lures compared to unrelated answers, qualitatively similar to the semantic relatedness effect in our view. Furthermore, the effect was present at both the 200 and 600 ms SOA levels, but was somewhat stronger at the shorter SOA. Just as was the case in the semantic priming literature (e.g., Neely, 1977), we interpreted this as indicative of an automatic spread of activation through the memory network.

Note that even here it was important to address counting-based interpretations of these results, especially since Parkman (1972) had in fact considered a counting model for multiplication. A counter argument to our interpretation held that our participants might have counted up by multiples of the problem operands (e.g., for 7×4, counting 4, 8, 12, 16, and so forth), and therefore would have "encountered" confusion, table-related answers en route to the correct answer. This "encounter" would presumably have involved registering the multiples in the internal counter as the count proceeded to its final value and could easily have led to slow rejection (or false recognition) of the lure answer. But our procedure carefully made sure that half of all false answers, table-related as well as unrelated answers, were larger than the correct value, and half smaller than the correct answer. No differences were found when "too small" versus "too large" answers were analyzed separately, for either table-related or unrelated answers. Thus there was no evidence in the results of any counting-based performance for simple multiplication. Instead, the confusion and priming results pointed quite clearly toward retrieval from an interrelated network of information, a network that was accessed via the process understood from semantic research to be spreading activation.

3.2. Switch from Counting to Memory

As noted above, the evidence that first graders count when they first begin to do simple addition seemed quite convincing, both based on Groen and Parkman's (1972) research as well as many educational studies of children's number knowledge upon entering the formal educational system (see Bisanz, Sherman, Rasmussen, & Ho, 2005, for a review). In general, entering first graders know their numbers, are good at enumeration (within limits), and therefore are routinely taught addition by referring to their existing knowledge of counting.

Taking this as a beginning point, we conducted a series of developmental studies, examining performance to simple addition problems across a range of years in elementary and secondary school (Ashcraft & Fierman, 1982; Ashcraft, Fierman, & Bartolotta, 1984; Hamann & Ashcraft, 1985). Results from children in first grade replicated the Groen and Parkman findings, adding to the already strong evidence showing counting based on the minimum addend. Beginning with fourth grade, however, we found the characteristic exponentially increasing pattern that we had identified with adults. Later grades continued to show this exponential pattern, although it became shallower across grades (and faster overall, of course). Interestingly, in our third grade sample, half of the children showed the exponential pattern, and half the linear *min* pattern found for younger children. This suggested that the transition from counting to memory retrieval was well under way by third grade. Whatever the metric was that shaped the memory representation, it seemed to begin operating during the elementary school years.

We advanced a model of this developmental process in Ashcraft (1982), a model that claimed there were two explicit and parallel processes by which children could arrive at the answer to a simple addition problem. Early on, in the first two elementary grades, children were predicted to rely overwhelmingly on the counting process, as identified by Groen and Parkman (1972), although even here there is a developmental trend—children switch from the rudimentary ''count all'' process to the more efficient ''count by *min*'' process, usually by first grade (Groen & Resnick, 1977). By third grade, a sufficient number of addition facts are being retrieved from memory, at least for some children, that the problem size effect starts to show more adult-like patterns, and presumably within each child there is a mixture of retrieval for some problems and counting for others. Then as more and more problems achieve sufficient strength in memory, there is greater and greater reliance on retrieval, and adult-like patterns for the problem size effect for the majority of children. Importantly, for any child and for any problem, the model predicted that performance was determined by the faster of the two parallel processes, the memory retrieval process and the procedural process of counting.

As learning continues, the model predicted change in both the declarative network of stored facts—essentially further strengthening of the memory network—and further elaboration of the procedural component, including an increase in the child's knowledge of algorithms and rules, informal procedures, and the like. Although precise chronometric predictions were beyond the model's scope, the intent was clear; at every developmental stage, and for every problem, there was the possibility that performance could reflect retrieval from a network of stored facts, or reliance on counting or other procedural knowledge. In all cases, in a response latency situation, performance would be governed by the faster of the two parallel processes.

3.3. The Source of the Problem Size Effect

Buried beneath these issues of the nature of the memory representation and its development is the overriding question that has puzzled investigators since the early studies in this area of investigation—what causes the problem size effect? The source of the effect for young children who count is clear—it is the iterative counting process itself, the count-on process of incrementing by ones. But when retrieval replaces this process, and when older children and adults become fluent retrievers, what is the reason for the continued increase in latency as the problems grow larger? Why does this increase characterize all four arithmetic operations, every age group that has been studied, and participants in every country that has been tested? What characteristic of the memory representation leads to this effect, or what characteristic of the learning of arithmetic shapes the memory representation such that this effect is the invariable outcome?

3.3.1. Strength in Memory

One likely explanation, we hypothesized, involved strength of the representation in memory, in particular the strength of problem representation as established during the elementary school years. That is, we thought that problems might vary in how strongly they are represented in memory, possibly as a function of the way they are taught in school. Accordingly, in Hamann and Ashcraft (1986), we tabulated the frequency with which simple addition problems appeared in elementary school textbooks. Texts from three publishers were examined for grades K through 3, with the frequency of occurrence tallied for each of the 100 basic facts. The telling result was that problems with operands of 2, 3, or 4 occurred far more frequently than those with operands 5–9. Interestingly, problems with a 0 or

1 as an operand were also fairly low in frequency. In other words, problems containing larger values are underrepresented in textbooks, compared to problems with small values (interestingly, the same pattern was found in a similar tabulation reported by Clapp, 1924). Problems with 0 or 1 as an operand tend to be taught by means of a rule: a number plus 0 is the number; for any number plus 1, just count up 1. But problems with operands 2–9 are taught by repetition, and our tabulation revealed that this repetition is applied differentially depending on the size of the operand.

Thus, there was evidence in the textbooks for the assumption that larger addition problems might indeed be stored in memory with lower strength—problems like $7 + 9$, invariably slower in latencies for all ages, simply occur far less frequently in elementary school than problems like $3 + 2$. As such, with lower strength in memory, it would be straightforward to predict that larger problems would be retrieved more slowly and with greater probability of error. As it happens, there is also a "small fact bias" in textbook presentations of multiplication problems (Ashcraft & Christy, 1995) for grades 1–6, just as there is a strong problem size effect in multiplication. Although we acknowledged that other factors, such as reconstructive strategies, contributed to the problem size effect, we remarked that "it seems inconceivable that the variations in frequency [in textbooks] would be unrelated to performance" (Ashcraft & Christy, p. 416).

3.3.2. Errors

Just as latencies increase with increasing problem size, so do errors; indeed, the problem size effect is routinely defined as the joint increase in both RTs and errors across increasing problem size. A natural side effect of decreased strength, of course, would be an increase in errors to large problems. But errors provide more interesting evidence than merely an alternative dependent variable to RTs.

As an example, Siegler and Shrager (1984) proposed that children's answers, correct answers as well as errors, are stored in memory as learning proceeds, not an unreasonable assumption (e.g., Logan, 1988). When a problem is presented for solution, the greater the history of errors associated with an operand pair will lead to greater difficulties in retrieval, for example, slower RT and more reliance on reconstructive strategies, as compared to problems with lesser histories of errors. In Siegler and Shrager's terms, a problem with a lesser history of errors will have a more peaked "distribution of associations," literally a more compact distribution of values around the correct answer. In such a scheme, the correct answer is more likely to reach the threshold for retrieval, and be advanced as the correct answer fairly rapidly. A problem that has experienced more errors in its history has a flatter distribution of associations, one that is more widely spread, with many more associations to error responses. Needless to say, the latter situation yields slower performance because the correct answer is less likely to have achieved threshold for retrieval. With less frequent successful retrieval, there is a greater reliance on other procedures such as counting or other reconstructive methods, or else occasional retrieval of incorrect answers. In the present context, we would expect such flatter distributions for larger problems, since those would have been learned to a lower criterion, and stored with lower strength in memory. Thus, despite the heavy reliance on memory retrieval in the model as the natural endpoint of a developmental process (see also Siegler & Jenkins, 1989), there was a natural inclusion of learning history that provided a principled account to explain the consequences of memory strength and developmental patterns of error.

4. Alternative Explanations

4.1. The Network Interference Model

Later developments in this field of research continued to explore the ramifications of error patterns on memory models. A prime example was the network interference model proposed by Campbell (1987). Campbell's emphasis in this model was based on the realization that errors to simple multiplication problems typically are table-related multiplication answers, for example, 24 as the erroneous answer to 8×4 (Campbell & Graham, 1985). As such, his network interference model proposed that retrieval from the network representation was an issue of activating candidate answers in the network, then discriminating the correct answer from among the set of activated candidates. Some operand pairs activate a limited set of candidates, so experience less interference, whereas some activate a larger set of candidates, so experience greater interference. Importantly, in Campbell's analysis, larger problems receive less practice and experience more errors during learning, leading them to have larger candidate answer sets in the memory representation. As a consequence, they experience greater interference during a retrieval attempt than do smaller problems.

The Campbell model represented clear theoretical progress in the field, in that it provided a principled account for adults' errors as well as their RT profiles; indeed, according to Zbrodoff and Logan (2005), the network interference model "remains the best explanation of memory-based arithmetic performance" (p. 338). For present purposes, it is important to note that Campbell's model took as a given that adult performance was based heavily on retrieval from a memory representation, with time differences in retrieval attributed to memory phenomena rather than processes related solely to counting. Note also that it was exactly those larger problems that experienced greater interference from the larger candidate answer sets, that is the larger problems already identified as those lower in memory strength. In important respects, then, the strength- and error-based approaches are entirely compatible explanations of the problem size effect; problems learned to a lesser degree because of lower degrees of practice are stored with less strength, hence have greater probability of error during testing.

4.2. Strategy-Based Responding

In a very real sense, memory models in this area have always included reconstructive, strategy-based processes as part of their explanations. Indeed, researchers have always acknowledged an important role for some reconstructive strategies that augment or supplement retrieval for adults, and certainly have emphasized such strategy-based explanations in developmental contexts. This combination of reconstructive and reproductive approaches characterized Groen and Parkman's (1972) original thinking, with their direct access plus counting model for adults, and it was certainly present in our initial work (Ashcraft, 1982; Ashcraft & Battaglia, 1978). In fact, Ashcraft explicitly included both a network representation of facts to support retrieval and a procedural "knowledge about arithmetic" component to accommodate the variety of strategies that children (and adults) use when performing simple arithmetic. It is equally true that the early memory models emphasized memory retrieval over reconstructive processing, and asserted that the bulk of adults' performance could be explained by means of memory mechanisms.

A reassertion of the importance of reconstructive, strategy-based performance appeared in the work of LeFevre in the mid-1990s. LeFevre, Sadesky, and Bisanz (1996) presented the simple addition facts to adults, had them furnish the correct answer, and then tell the investigators how they had solved the problem; LeFevre, Bisanz, et al. (1996) did the same with multiplication facts. In both cases, a significant proportion of the larger problems were reported to have been solved by means of strategies, for example, transformations in order to retrieve a well-known fact (e.g., transforming $4 + 7$ to $7 + 3 + 1$), counting, and the like; in fact, transformations accounted for some 85% of the nonretrieval trials. Some 29% of all simple addition trials were reported to have been solved by a process other than direct retrieval; in LeFevre, Bisanz, et al., the comparable values for multiplication were 12 and 19% (Experiments 1 and 2, respectively). Fully 81% of the participants in the addition study reported using at least one nonretrieval strategy, and a comparable number reported nonretrieval processes in multiplication. Invariably, when nonretrieval trials were segregated, their RTs were slower; indeed the problem size effect was reduced, and virtually flat, when only retrieval trials were considered. The implication of these results was that the use of retrieval was characteristic especially of small problems, that larger problems relied heavily on relatively slow strategies and procedures, and that it was those slower strategies and procedures that were largely responsible for the problem size effect.

Our concern with LeFevre's demonstrations was not that there seemed to be evidence for procedural processing in simple arithmetic; as noted above, all of the models in this area, from the very beginning, had acknowledged a role for procedural processing. Our concern, instead, involved the empirical procedures used to obtain the strategy reports in LeFevre's studies. Rather than merely asking participants to report "how did you get the answer to that problem," in a neutral fashion, LeFevre's procedures supplied participants with choices and examples of problem solution methods; for example, "What do people do when asked to add 9 + 6? You could just remember the answer, 15. It just sort of pops into your head. You could figure the answer out by counting. You think 9, and then 10, 11, 12, 13, 14, 15. You could figure it out using a special trick. You could remember that 10 + 6 = 16, so 9 + 6 has to be just one less. Or you could solve it in some other way" (LeFevre, Sadesky, et al., 1996, p. 219).

Our view (Kirk & Ashcraft, 2001) was that this sort of instruction was prone to difficulties. In particular, we felt that giving choices and examples introduced the possibility of bias and demand, essentially communicating to participants that they should be reporting strategies of just the sort being suggested, and furthermore that they should be aware of their problem solving method and should be able to report it. The former would be outright bias and demand, of course. The latter is suspect, to the degree that processing is automatic, given widely shared assumptions that verbal reports are only valid if the information being reported had entered into short-term memory and been attended to (e.g., Ericsson & Simon, 1993).

To test these possibilities, we replicated the LeFevre, Sadesky, et al. (1996) procedure and also included three other groups. One group got instructions that biased the verbal reports toward retrieval; "You could just remember the answer, 15. It just sort of pops into your head. That is how adults usually solve problems of this size. Or you might solve the problem by using a strategy. Of course, adults almost always just remember the answer to problems of this size, and we would like to know more about that process." Another group got instructions biased toward strategy reports; "You could figure the answer out by counting. You think 9, and then 10, 11, 12, 13, 14, 15. You could figure it out using a special trick.... Or you could solve it some other way. Surprisingly enough, many adults do use strategies, even when solving problems of this size, and we are interested in knowing more about that. Or you could just remember the answer, 15. It just sort of pops into your head" (all quotations from Kirk & Ashcraft, 2001, p. 160). We also included a silent control group that merely performed the RT task without making verbal reports, a condition missing in the LeFevre reports.

Not surprisingly, verbal reports conformed to the biasing instructions that participants received, both in addition and multiplication; for addition, the retrieval bias group reported using retrieval 91% of the time, the replication group reported retrieval on 55% of the trials, and the strategy bias group reported retrieval only 38% of the time. More critically, the RT profiles of the retrieval bias group conformed to those of the silent control group. The replication group, on the other hand, exhibited somewhat slower RTs on the largest set of problems, and the strategy bias group showed considerably slower RTs on the same large problems. In short, reported solutions and actual arithmetic performance were dramatically influenced by the bias in instructions; the instructions from LeFevre, Sadesky, et al. (1996) led to much more frequent reports of strategy use than our retrieval bias group. When no reports were requested, in our silent control group, RT performance was virtually identical to the group given a bias to report retrieval. Thus, biased instructions not only influenced the nature of the verbal reports, they also influenced actual performance, as measured by RTs.

A literal-minded conclusion, based on the similarity of our RT results for the silent control and retrieval bias groups, is that 91% of simple addition performance is accomplished via retrieval, instead of the 71% value obtained in LeFevre, Sadesky, et al. (1996; a comparable conclusion for simple multiplication is 96% retrieval, from Kirk & Ashcraft, vs the 88 and 81% values in LeFevre et al., Experiments 1 and 2). A more generous conclusion is that some small but nontrivial amount of performance on simple addition and multiplication is accomplished via nonretrieval by Western adults, especially on large facts. Note, however, that "nonretrieval" here meant not relying on *direct* retrieval; the bulk of "nonretrieval" trials in the LeFevre et al. report involved transformations, in which participants solved from known facts (i.e., transforming 4 + 7 into 7 + 3 + 1). In other words, it was still the case that retrieval was central to the bulk of processing, although for large problems this might be referred to as "opportunistic" retrieval of more easily retrievable or accessible facts. We return to this notion later, in the overall conclusion to the chapter.

Our strong conclusion in Kirk and Ashcraft (2001) was that any procedure that provides choices and examples (see also Campbell & Xue, 2001) in soliciting verbal reports runs a serious risk of bias and demand. This is not to say that verbal reports cannot be successfully obtained, in our view (e.g., Seyler, Kirk, & Ashcraft, 2003), but merely that such reports must be collected carefully, with serious attention to issues of reactivity, bias, and demand. It is not clear, however, that this admonition is being heeded in more recent work with verbal reports.

5. Evidence from Cognitive Neuroscience

Mathematical cognition has begun to attract serious attention as a research area from those using modern cognitive neuroscience methods of investigation, prominently ERP, positron emission tomography (PET), and functional MRI (fMRI) scanning techniques. Some of this work has focused primarily on identifying brain regions or structures involved in mathematical processing, important to be sure but not always useful in advancing theoretical perspectives about cognitive processing. A few studies, however, have tackled issues of processing and representation, and provided important supportive evidence for conclusions discussed earlier. A brief summary of this work is provided here (see Dehaene, Piazza, Pinel, & Cohen, 2005, for a review and an integrative model).

5.1. Arithmetic Operations

Dehaene, Tzourio, Frak, and Raynaud (1996) tested participants on number comparison and multiplication tasks, using PET scans. They found activation in the occipital regions in all tasks, due to visual processing of the stimuli, as well as activation in several left hemisphere regions. The results indicated that the left basal ganglia were involved in storage and retrieval of rote multiplication facts, whereas parietal areas were involved in problem solution whenever direct retrieval failed (Dehaene et al.). Similarly, in Chochon, Cohen, van de Moortele, and Dehaene (1999), fMRI results showed largely left hemisphere parietal activation during multiplication, but ‘‘intensely’’ bilateral parietal activation during subtraction. Kazui, Kitagaki, and Mori (2000) also found parietal region activation for single digit multiplication, as well as frontal region activation. Interestingly, the same regions were also activated to a greater extent under serial subtraction, as were bilateral prefrontal and right hemisphere parietal regions. The additional areas of activation were assumed to be active because of the additional calculation processes required for subtraction (Kazui et al.). Finally, Delazer et al. (2003) trained participants on complex multiplication problems (two digit × one digit problems) for 1 week, then tested them on trained and untrained problems using fMRI. Performance on untrained problems involved more activation in the frontal regions, possibly related to working memory processing, whereas trained performance resulted in more activated parietal regions. Within the parietal lobe, a shift from the intraparietal sulcus for untrained problems to the angular gyrus for trained problems was also observed.

These results fit well within Dehaene's (1992; Dehaene et al., 2005) triple-code theory of number processing, a theory that posits three different types of representations involving number; a quantity system, a verbal system, and a visual system. The quantity system is thought to be a nonverbal semantic representation of the size of numbers, including the distance relations between numbers that subserves comparisons and approximations; this system appears to correspond to the bilateral horizontal segment of the intraparietal sulcus (HIPS). For the present context, approximate calculations involving differences in split might be expected to rely on this number system. The verbal system is the system in which numbers are represented lexically and phonologically, as in any other type of word, and is the system for written and auditory input and output; this system corresponds to the left angular gyrus. Dehaene et al. suspect strongly that multiplication, with its learning history especially tied to rote rehearsal, would depend heavily on this verbal system. Third, the visual system is the one in which numbers can be encoded as Arabic or other written forms and is responsible for multidigit operations; this corresponds to the posterior superior parietal system. In general, note that all of these systems rely heavily on the parietal lobes; indeed, Dehaene et al. postulate a "three parietal circuit" model for essentially all number processing tasks and settings.

Although these studies seem to have isolated regions and structures essential to number processing, they do not speak directly to issues of timing or strength, hence do not provide illumination on issues like the problem size effect. An important ERP study on multiplication, however, has done exactly that, a study reported by Jost, Beinhoff, Hennighausen, and Rosler (2004). These investigators conducted a careful study of the problem size effect in multiplication, examining problems with a zero operand (e.g., $n \times 0$), and small versus large operand problems (both operands ≤ 5 for small, and >5 for large); zero operand problems were treated as a separate category on the general evidence (e.g., Miller et al., 1984; Stazyk et al., 1982) that such problems are solved via the "zero rule" ($n \times 0 = 0$) rather than via retrieval.

The behavioral evidence showed the classic problem size effect, with zero problems faster than nonzero problems, and small facts faster than large facts. Second, they found a P300 ERP pattern, which peaked about 450 ms after stimulus presentation, followed by a subsequent negative slow wave pattern. The P300 amplitude was highest for the nonzero multiplication facts, and somewhat smaller for zero multiplications (and lowest for a "storage" condition that involved only storing the operands in memory, with no arithmetic computation required). Furthermore, the slow negative wave was most pronounced for large multiplication facts, suggesting a higher mental workload, and was intermediate for small and zero multiplications. In sum, the pattern of results suggested, as do the RT and verbal report data presented earlier, that different processes are used for different categories of problems. Zero problems tend to be solved via the simple zero rule, with a different slow negative wave pattern. Larger multiplication facts showed a more pronounced negative slow wave pattern than smaller facts, suggesting to the authors that "less practiced problems involve other processes than pure fact retrieval" (Jost et al., 2004, p. 183).

Interestingly, Jost et al. speculated that the nonretrieval strategies used for larger problems were activated only when retrieval had failed. This speculation was based on evidence that the obtained P300 amplitudes (but not the topography of the subsequent slow wave patterns) were the same for small and large problems. In other words, according to some investigators, P300 amplitude serves as an index of anticipated task difficulty, that is, how demanding the participant expects the trial to be based on early assessment of the stimulus (e.g., Wilson, Swain, & Ullsperger, 1998). If so, then participants apparently expected both small and large problems to be equally demanding, based on the similarity of P300 amplitudes. Only later, during processing, did they discover that larger problems were more difficult, thus generating the more pronounced slow wave patterns for large problems. If such a result can be replicated, and extended to other operations, this may indeed provide an answer to a long-standing debate in the literature, whether retrieval- and strategy-based solution methods proceed in parallel, in racehorse fashion, or whether the strategy-based method is typically invoked only after retrieval failure.

5.2. Split Effects

Several ERP-based studies have also been reported on the split effect, the decision stage variable we originally manipulated in Ashcraft and Battaglia (1978). Recall that when arithmetic problems were given incorrect answers, greater discrepancies between the correct and incorrect answers led to faster rejection of the problem; with a pronounced discrepancy, rejection can even be faster than acceptance of the true version of the problem, suggesting a "short-circuiting" of the normal solution process (Ashcraft & Battaglia; Ashcraft & Stazyk, 1981). Such results have suggested a magnitude-based decision process to several investigators, and the bulk of the recent ERP work furnishes evidence in support of such a mechanism.

As an example, Niedeggen, Rosler, and Jost (1999) showed simple multiplication facts for true/false judgments, where incorrect answers differed from correct by ± 1, 2, or 3, and found a comparable N400 effect to that found with semantic incongruities. In a second experiment, false multiplication answers were either wrong by ± 1, were the incorrect answer under addition (e.g., $4 \times 7 = 11$), or were table related to the multiplication fact (e.g., $4 \times 7 = 21$). All of the false answer conditions elicited the N400 effect, although this negativity was less pronounced if the solution had already been partially activated by one of the problem operands, that is, if the problem had been given a table-related answer. Similarly, Niedeggen and Roser (1999) found higher N400 negativity for unrelated answers than for table-related answers, and larger amplitude of the late positive component (LPC) of the ERP as the split grew larger. Along with other results (El Yagoubi, Lemaire, & Besson, 2003; Núñez-Peña & Escera, 2007), these studies suggest a magnitude-based mechanism sensitive to the split effect, such that large split problems are solved with an approximate calculation strategy, with different ERP profiles than those obtained for the exact calculation strategies used on small split problems.

6. Current Directions

6.1. The Role of Working Memory

As is commonly known, working memory has assumed a significant role as an important predictor of cognitive performance in the past 30 or so years, especially since the articulation of Baddeley's multicomponent theory of working memory (e.g., Baddeley, 1996; Baddeley & Hitch, 1974), and has been shown empirically to be strongly related to task performance in a variety of important cognitive domains (see Miyake & Shah, 1999). Although there is not a large body of research in mathematical cognition on the role of working memory in mathematical tasks, the existing research does show quite uniformly that working memory plays a substantial role in performance (see LeFevre, Destefano, Coleman, & Shanahan, 2005, for a review). Except for situations in which straightforward, automatic fact retrieval is responsible for performance, working memory plays a central role in mathematical performance.

A single example suffices to demonstrate this point. Seyler et al. (2003) tested college adults on the simple subtraction facts. Unlike the gradually increasing problem size effects found for addition and multiplication, however, we found a sharp increase in RTs and errors beginning at a minuend of 11 (in subtraction, minuend minus subtrahend equals remainder; for $13 - 8 = 5$, the minuend is 13). We suspected strongly that the unusual increase was due to reliance on strategies and reconstructive processing rather than retrieval from memory. To confirm this, we collected verbal reports in Experiment 3, merely asking participants to tell us how they solved the problems, and providing no choices or examples; a silent control condition was also included, to make sure that verbal reporting did not alter the basic processing under investigation. There was indeed substantial reporting of strategy use for the larger problems, in line with previous reports (e.g., Campbell & Xue, 2001; LeFevre, Sadesky, et al., 1996). Recent work by Campbell (2008) confirms that the bulk of this strategic processing in subtraction consisted of converting large subtraction problems to the corresponding addition fact (e.g., for $13 - 8$, solving $8 + \_ = 13$).

We reasoned that such reliance on strategies must surely burden working memory for those larger facts, in comparison with relatively fluent and rapid retrieval of the smaller subtraction facts, which seemed to rely hardly at all on strategies and was probably representative of genuine fact retrieval. Thus in Experiment 4, we evaluated the contributions of working memory to performance in two ways. First, we embedded the subtraction problems within a dual-task setting. Participants performed subtraction alone, a letter recall task alone, and then both tasks together. The point of this, of course, was to see if concurrent letter recall, especially when it became difficult, and subtraction, especially on the larger, more difficult facts, yielded degraded performance due to competition for working memory resources. Second, we pretested all participants on a working memory span task and categorized them into low, medium, and high capacity groups.

As predicted, when the letter task and subtraction were performed simultaneously, there was a significant increase in errors, especially when doing large subtraction facts. This of course indicated that those large facts depended more heavily on working memory resources for their performance, and thus impacted the letter recall task more when it was performed simultaneously with subtraction. Importantly, this increase in errors under dual-task conditions was especially pronounced for the low capacity group, but was only minimal for the group determined to have high working memory capacity. Thus, preexisting working memory capacity was also a significant factor in how participants fared when faced with the dual-task setting. Those with high capacity dealt reasonably well with the extra load placed on them by the letter recall task and the large subtraction facts, committing only about 20% errors in the dual-task setting (vs about 7% in the single task condition). Those with low working memory capacity suffered, however, committing almost 40% errors in the same condition (and only 16% in the single task condition). Clearly, even the simple subtraction facts require the resources of working memory for performance, and participants with lower working memory capacity suffer because of it.

The importance of working memory to mathematical performance increases, naturally, as the problem being solved increases in complexity, both in terms of the size of the operands involved in the computations and in the number of steps or components in the problem. Carrying in the addition operation, for example, has been shown to place demands on working memory (Ashcraft & Kirk, 2001; Furst & Hitch, 2000); in algebra problem solving, errors tend to cluster at points in the problems' solutions at which working memory load is expected to be highest, for example, where intermediate values or subgoals need to be held in memory (e.g., Ayers, 2001; Campbell & Charness, 1990).

Although this general relationship seems to be firmly established, details of the relationships are not yet entirely clear. That is, Baddeley's (1996) model provides mechanisms by which phonological, visual, and spatial codes may all be involved, in various ways, in mathematical problem solving. Some generalizations have been reached concerning math processing and the mechanisms in Baddeley's model. For example, interim results in complex calculations seem to be held by the phonological loop of the working memory system (Furst & Hitch, 2000); the visual–spatial system seems to be critical when problems are presented vertically, but verbal codes are more important if the same problems are presented horizontally (Trbovich & LeFevre, 2003). On the other hand, some studies show no relationship between verbal loads and performance on simple arithmetic performance in a dual-task setting (e.g., De Rammelaere, Stuyven, & Vandierendonck, 2001), whereas others do find such relationships (e.g., Lee & Kang, 2002).

It may well be that such conflicting results simply reflect the fact that insufficient results have yet been made available on these issues, and that further research will yield agreement. It may also be that there is not going to be a simple answer to such questions, to the degree that every participant's underlying performance is in fact an idiosyncratic mixture of retrieval and strategies, with some strategies depending on verbal-based processing, and possibly some on visual processing. Regardless of these specifics, it is manifestly clear that math processing, especially as the task grows in complexity, is dependent on working memory. Indeed, given that difficult math seldom approaches the level of automaticity that other everyday cognitive tasks do, it is probably even more important to investigate and understand the role of working memory in math performance.

6.2. Math Anxiety

Math anxiety is usually defined as an emotional reaction, ranging from tension up through dread, experienced in situations involving math and number. The situations can be formal, as in classroom settings when a test is being administered, or informal, as in a restaurant when a person's share of a bill has to be figured. An extensive literature exists on the personality and educational variables that correlate with math anxiety (see Hembree, 1990, for a meta-analysis); most prominently, math anxiety correlates strongly with test anxiety, is negatively related ($r = -0.31$) to math achievement and is negatively correlated with math grades and pursuing elective math coursework in high school and college.

We wondered if math anxiety was merely a personality variable with long-range educational and personal impact, or if it also had consequences on the actual doing of math. In several early studies, we determined that one's math anxiety had little if any impact on performance to simple addition and multiplication facts, but indeed did affect performance to somewhat more complex arithmetic performance, for example, two-column addition, especially with carrying (Ashcraft & Faust, 1994; Faust, Ashcraft, & Fleck, 1996). Given that carrying had also been identified as a math process dependent on working memory, we decided to apply the dual-task procedure to a study of math anxiety.

In Ashcraft and Kirk (2001), we had our participants perform mental addition, including two-column addition problems with and without carrying. They also performed a letter recall task, either by itself or in a dual-task setting, in combination with the addition task. All participants showed modest effects of the dual task, of course, especially when the arithmetic processing became difficult due to carrying. But in the difficult condition, holding six random letters in working memory, performance deteriorated on carry problems especially dramatically for the high math anxious group; their errors reached 40% in this difficult condition, versus only 20% for the low anxious group (compare with a 10% error rate in the no carry condition for all groups, and no more than 10% errors in all other conditions involving two random letters). It was as if being high math anxious had turned the task from a dual task into a triple task setting—interference was not just due to addition plus random letters in working memory, but was due to addition plus random letters plus math anxiety (for similar work on the effects of pressure on math performance, see Beilock, 2008).

Recently, Guillaume (2008) conducted a study on incidental learning, using the true/false verification task with simple addition. Participants of varying degrees of math anxiety saw either true problems or false problems with splits ranging from ± 1 up to ± 9, either once in the session or nine times. At the end of the session, during a surprise recall task, high math anxious participants were far more likely to remember the false answers to the small and medium split problems they had seen earlier than the low anxious participants were, even though both groups spent approximately the same amount of time verifying those problems during the original blocks of trials. The recall effect, furthermore, was only true for those high anxious participants who were also low in working memory span, suggesting an important relationship between math anxiety and working memory deserving of further exploration.

7. Concluding Remarks

7.1. Resolving the Debate: Strength and Strategies

The debate over the source of the problem size effect seems to have come to a standstill. Three competing explanations have been advanced, one based on strength of problem representation in memory, one based on the history of errors and the competition of erroneous answers during retrieval, and one based on reconstructive, strategy-based responding.

A poor way to resolve this debate, in our view, is to continue to pursue the research using current methodologies. The limitations of these methodologies have become clear. Another round of experiments using RTs and error rates is unlikely to clarify the debate; we will find, once again, that RTs and errors increase with increasing problem size, with no definitive explanation for the increase. Obtaining verbal reports, even if done properly, will again demonstrate more reported strategy use for larger problems. But the underlying reason for the increase in errors and the greater reliance on strategies, whether lower strength or some other factor, will remain at a distance.

Instead, and until potentially disambiguating evidence such as results from eye-tracking, ERP, or scanning investigations becomes available, we suggest the following. Consider strength in memory as the basic variable underlying the memory representation for arithmetic facts, and as the most basic variable to have been proposed as the source of the problem size effect. This is a rather straightforward proposal if one believes the assertion that people do indeed store information in long-term memory, and that the way the information is stored influences how it is retrieved. If an item—whether an arithmetic fact, a word, an image, or any other bit of information—is stored with some degree of strength into a long-term memory representation, then there is some likelihood that it can be retrieved. Strengthening the representation of the item in memory, or the number of times it is stored (e.g., Logan, 1988) increases its retrieval probability. Conversely, storing the information weakly leads to a lower probability of retrieval. Note that even occasional repeated errors on a problem would lead to storing the wrong answer too, with strength proportional to its frequency of occurrence.

Under other circumstances—say word retrieval—lower strength might lead to unsuccessful retrieval, and a "don't know" response (ask an undergraduate what the meaning of "avuncular" is, for example). In arithmetic, however, there are other means for obtaining an inaccessible or unretrievable answer. If the sum of 9 + 8 is not stored in memory, or is stored so weakly that it is even momentarily inaccessible, then a variety of backup strategies, including (lengthy) childlike counting, are available for reconstructing the answer. For reasons still not adequately explained, tie problems are easily learned and seem to be quite accessible, even for young children—thus solving 9 + 8 by transforming it to 8 + 8 + 1 is a ready option for all. Such "opportunistic" transformations may, in some cases, substitute for storage of 9 + 8 in memory, just as opportunistic solution of large subtraction facts by means of addition seems to account for a considerable part of adults' simple subtraction (Campbell, 2008).

The price of relying on opportunistic retrieval of accessible nearby facts, however, is the price of working memory involvement; these solutions either consume additional time as compared to direct retrieval, generate additional errors, or require more conscious processing. As a math problem becomes more complex, hence more demanding on working memory (e.g., for multistep problems), spending some of those limited resources on simple arithmetic facts when they are needed for higher level processes may be quite costly.

Notice the consequences of such a strength-based scheme. Problems that eventually achieve sufficient strength can be retrieved. Problems that do not achieve sufficient strength can still be solved, but will rely on some reconstructive method, which will be slower than retrieval and generally more prone to error. Thus, lower strength, already identified as a characteristic of larger problems, will be tightly linked with the probability of errors, yielding a greater history of errors for larger problems. Lower strength likewise is tightly linked with greater use of reconstructive strategies. Given that such strategies generally involve multiple steps, and lengthier processing time, it is not surprising that they often generate more errors as well (we are far more likely to count inaccurately on a large problem), amplifying the error history for the problem being solved.

It is clear that there are large variations in the mental processes called forth for problem solution. These processes vary across and within individuals, but just as importantly across and possibly within problems; a single individual may routinely solve some large problems via retrieval and others by reconstructive means, whereas another may vacillate between retrieval and strategies even on a particular problem, sometimes retrieving $9 + 8$ directly, sometimes transforming it to $8 + 8 + 1$ to take advantage of the easily retrieved tie problem, and so forth. One need only imagine a model in which errors and useful strategies are associated with problems along with correct answers, to the degree that each of these is stored, each with its own particular strength. On any particular solution attempt, the governing process for that trial would be the associated information and process that was accessed, whether retrieval of a correct or incorrect answer or a strategy. What we have outlined here is the essence of the family of models proposed by Siegler (e.g., Siegler & Jenkins, 1989; Siegler & Shipley, 1995; Siegler & Shrager, 1984), in which answers, including errors, and strategies all are stored in memory, each with an associative strength. Fundamental to the model, however, is the basic notion of strength as the parameter governing both correct and incorrect retrieval, and also the parameter governing whether performance depends on retrieval or a reconstructive strategy. Also fundamental, though not explicit in Siegler's work, is the working memory component, essential when processes other than direct, automatic retrieval operate.

One factor not yet resolved is whether the retrieval process and the reconstructive-based solution process operate in parallel, in a classic race-horse model fashion, or whether the reconstructive method is invoked only when direct retrieval fails. Our early model (Ashcraft, 1982) suggested a parallel process for these two solution methods, based on the pattern of RTs to problems with large splits. This may be in error, to the extent that additional ERP data in line with the Jost et al.'s (2004) conclusion can be obtained. On the other hand, it may be difficult to resolve this issue, to the degree that some problems may have such a low strength associated directly with an answer that, functionally speaking, there is only a reconstructive solution method available for problem solution. In such a situation, the distinction between parallel processing and reconstruction-after-retrieval failure seems empty.

It would be useful, furthermore, to see additional evidence, say from fMRI studies, on other aspects of reconstructive-based performance. That is, if adults rely on strategies for a substantial amount of processing, even for the basic arithmetic facts, then this should involve working memory, since it is widely assumed that these reconstructive processes involve the operation of various working memory processes. It should be possible to see (literally) evidence of such processing in fMRI scans when, say, larger addition, subtraction, or multiplication facts are being solved, although apparently no such evidence is currently available. Likewise, if some arithmetic performance relies especially on visuospatial processing, as suggested in Dehaene et al. (2005), then further scanning evidence would be useful in cementing that claim.

7.2. The Changing Problem Size Effect

We conclude with one final point, the relative contributions of strength, errors, and strategies to the problem size effect, and the challenge of recent work, showing more use of strategies than had previously been assumed (e.g., LeFevre, Sadesky, et al., 1996). The work reviewed here, for the most part, has relied on classic cognitive methods to draw inferences about underlying mental processes, methods relying on RTs and errors primarily, but also verbal reports of solution methods. Our view is that applying such methods in further attempts to determine what the "true" percentage is for retrieval or strategy use is misguided. Although our reasons are speculative, they do have a degree of face validity.

We suggest that the very effect we seek to explain, the problem size effect, is changing across the years. That is, we suspect that the problem size effect, and the relative contribution of strength, errors, and reliance on strategies to its shape, is also influenced by cohort effects related to educational practice. As an example, Campbell and Xue (2001) reported significant cultural differences in performance to simple and complex arithmetic, with participants with a Chinese educational background showing much more efficient retrieval of simple arithmetic facts than those with a Canadian educational background. These differences were attributed to both educational and cultural differences, especially the emphasis placed on mastery of math in Asian schools (for similar results involving culture and cohort differences, see Geary, Salthouse, Chen, & Fan, 1996).

In comparable fashion, we might expect differences in samples across the years to the degree that educational and curricular changes have taken place, changes that result in de-emphasized learning and mastery of basic facts. Quite literally, we might expect that studies performed 20 years from now (or 20 years ago) would yield rather different results concerning retrieval and strategy use than contemporary results show. Indeed, a recent paper by LeFevre, Penner-Wilger, Pyke, Shanahan, and Deslauriers (2008) draws exactly this conclusion, based on a 20% decline in performance of university students on the French Kit, a standard assessment of arithmetic fluency, between 1993 and 2005. We may be seeking to characterize the basic problem size effect as one based exclusively on memory, or as one based on memory for a fixed or knowable percentage of the trials, when in fact the educational practice that our participants have experienced has been changing all along, de-emphasizing memory for arithmetic facts. Basing our theories on such a moving target seems ill advised. On the other hand, to the extent that such changes can be documented with cognitive techniques and measures, this may be one arena in which cognitive psychology can contribute an important bit of evidence to the ongoing national debate concerning mathematics education.

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CHAPTER FIVE

Highlighting: A Canonical Experiment

John K. Kruschke[1]

Contents

Abstract

Highlighting is a perplexing effect in learning, in which shared features are more strongly associated with early learned outcomes but distinctive features are more strongly associated with later learned outcomes. The effect has been widely observed with different stimuli, procedures, and application domains. It continues to discomfit many theories of learning. This chapter provides results from a "canonical" design in which the base rates of early and late outcomes are equalized. This balanced design yields data that pose a challenge to models that have relied on differential base rates of past designs to mimic highlighting. The data are available at the author's Web site as a test bed for models. A Bayesian data analysis is also reported that provides explicit posterior distributions over choice probabilities. The posterior distribution is also available online.

[1] The author's World Wide Web page is at http://www.indiana.edu/~kruschke/.

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1. Cue-Outcome Learning as a Window on Cognition

It is easy for a person to learn that when "ocean" and "arrow" appear on a computer screen, s/he should press the "F" key, but when "ocean" and "tulip" appear on the screen, s/he should press the "J" key. In a standard learning procedure, a person sees the cue words, presses the key s/he thinks is correct, and receives the correct outcome. After many repetitions, accuracy improves. This procedure and the finding that people are able to learn are, in a word, dull.

One fact that makes the exercise a little less dull is that cue-outcome learning in the lab is a distillation of a type of high-stakes learning that happens in real life. As examples: Physicians learn which symptoms indicate deadly diseases, and stock brokers learn which financial markers indicate times to buy or sell millions. If this sort of learning is to be understood by cognitive scientists, they need to study it in simplified and controlled laboratory experiments. Lab experiments can rarely impose consequences such as bankruptcy or death, however. The innocuous and bland laboratory procedures may therefore be described, in polite company, as less than scintillating.

What elevates cue-outcome learning from the banal to the fascinating is that people may learn, and respond to novel cues, in ways that are perplexing, if not downright bizarre. Although learners have blazed mental pathways from cues to correct outcomes, those pathways may be so convoluted that it is puzzling how humankind has blundered its way to the top of the food chain.

This chapter focuses on one puzzling phenomenon in cue-outcome learning, called *highlighting*. It is interesting because it violates (many) prescriptions for what a rational learner *should* do, and it is interesting because it deviates from what (many) learning theories *can* do. Highlighting is vexing because it crashes the parties of many established learning paradigms, when propriety would prefer to ignore it. But highlighting is also revealing, forcing theorists to find mechanisms that can explain it. Once revealed, the mechanisms may be seen to be fundamental aspects of learning, not just bad behavior.

After a brief review of previous work on highlighting, the primary goal of this chapter is to report new data from a "canonical" highlighting experiment. It is hoped that these data can serve as a test bed for models of learning. The data are available on the author's Web page, and so is the computer program for the experiment itself. The chapter also provides a novel Bayesian analysis of the data, unlike previous reports. The Bayesian analysis yields distributions of believable response propensities. These posterior distributions are also available on the author's Web page.

The chapter concludes with a brief discussion of the continuing challenges posed by highlighting for recent models of learning, including Bayesian learning models.

2. Highlighting

2.1. The Phenomenon

Suppose a person initially learns that when "ocean" and "arrow" appear on a computer screen, s/he should press the "F" key. The person subsequently learns that when "ocean" and "tulip" appear on the screen, s/he should press the "J" key. Notice that "arrow" is a perfect predictor of "F," and "tulip" is a perfect predictor of "J," whereas "ocean" is an imperfect predictor. Thus, there is a symmetry between the two responses, each having a unique perfect predictor, and sharing an imperfect predictor. Given this simple symmetry, it is reasonable to assume that the person learned the symmetry. This assumption can be assayed by testing the person with the single cue word "ocean." If the cue has been appropriately learned to be an equally imperfect predictor of the two outcomes, then the person should respond equally with the outcomes. Across many learners, however, there is a strong tendency to prefer the early learned "F" outcome. Unfortunately for learning theorists, this preference cannot be trivially explained as a generic primacy bias in response to ambiguous cues, because when learners are presented with the ambiguous cue combination "arrow" and "tulip," there is a strong preference for the later learned "J" outcome.

The phenomenon occurs for a variety of cues and outcomes and is not restricted to cues as words and responses as letters. Therefore, the cue-outcome structure is here redescribed with generic notation, abstracted from any irrelevant concrete instantiation. Early in training, the learner experiences cases of cues PE and I together indicating outcome E. This case is denoted I.PE $\rightarrow$ E. This case is trained until the learner knows it well. Then the learner is trained with cases of I.PL $\rightarrow$ L, in which cue PL and outcome L have not been previously trained. Notice that the cue structure is symmetric: Each outcome has a single perfectly predictive cue and the outcomes share the cue I. The only difference is that outcome E is trained *early*, and outcome L is trained *late*. Thus, cue PE is a *perfect* predictor of the *early* outcome, and cue PL is a *perfect* predictor of the *later* outcome, while cue I is an *imperfect* predictor. Interspersed training of I.PE $\rightarrow$ E and I.PL $\rightarrow$ L continues until both are learned well. Near-perfect accuracy is not difficult to attain. After training, when probed with cue I by itself, people are not impartial, instead strongly preferring outcome E. On the other hand, when presented with the cue pair PE.PL, people strongly prefer outcome L.

This torsion in people's preferences, going one way for I but twisting the opposite way for PE.PL, is called the "highlighting" effect. The appellation derives from two sources. First, highlighting refers to a theoretical interpretation of the empirical effect. In this interpretation, cue PL is attentionally highlighted during the learning of the cases I.PL → L. When experiencing I.PL → L, learners shift attention away from cue I, which is already associated with outcome E, toward cue PL. This theory will be explained more thoroughly later. The second motivation for the name "highlighting" is to juxtapose the empirical finding as complementary to the classic "blocking" phenomenon in associative learning (Kamin, 1968; Shanks, 1985), which can be at least partially explained by learned *inattention* to a cue, as opposed to learned highlighting of a cue (Kruschke, 2003b; Kruschke & Blair, 2000). Blocking will also be described in more detail later.

2.2. Highlighting Discomfits Theories of Learning

The highlighting effect is curious because people appear to have learned an asymmetrical cue-outcome structure despite the simple symmetry in the environment. What makes the phenomenon deeply interesting, however, is that most theories of learning cannot explain it.

Simple associative theories such as the Rescorla–Wagner model (Rescorla & Wagner, 1972) predict that after sufficient training, the associative weights reach asymptotic values that are symmetric. This symmetry emerges over several trials of later intermixed training. The initially learned association from I to E is reduced by subsequent cases of I.PL → L, because I has thereby occurred without E. The initially moderate association from PE to E increases when cases of I.PE → E recur, because cue I no longer predicts E very strongly. Eventually, the Rescorla–Wagner model accurately learns the symmetry, unlike people, who persist in the asymmetry even after fairly extended training. (Markman (1989) provides an alternative proof.)

Associative models that adjust cue salience or learning rates according to the novelty of the cues also fail to capture the effect. For example, a model was proposed by Shanks (1992) in which the salience of each cue is inversely proportional to a running estimate of its base rate. In other words, rare cues are more salient than frequent cues. While it is quite plausible that some form of novelty salience is at work in learning, and no doubt some phenomena do demand such a mechanism for adequate explanation, the particular mechanism in the proposed model does not account for effects closely related to highlighting (Kruschke, 1996). The novelty-salience model has not yet been fit to the new data reported in this chapter, but the model would probably have difficulty because, in the new experiment, what is initially a rare cue becomes a frequent cue, and *vice versa*.

Other variations of associative models set the learning rates of expected-but-absent cues to negative values (Markman, 1989; Tassoni, 1995; Van

Hamme & Wasserman, 1994). It is plausible that absent-but-expected cues are represented as explicitly absent in human learning, and perhaps some phenomena do demand such a representation for adequate explanation. But highlighting is not accounted for by these models. One difficulty with some of these models is that they do not propose a specific mechanism by which cue expectations are learned. Even when such mechanisms are specified, the new data presented in this chapter pose challenges for the models, because the long-run symmetry of the design (to be described later) implies that the absence of PE in I.PL trials may trade off symmetrically with the absence of PL in I.PE trials.

Various Bayesian models of learning fail to capture the effect. Several Bayesian models, such as the rational model (Anderson, 1990, 1991), the Kalman filter (Dayan, Kakade, & Montague, 2000), and sigmoid-belief networks (Courville, Daw, Gordon, & Touretzky, 2004), assume that all instances, regardless of their time of occurrence, are equally representative of the underlying cue-outcome association. In other words, the models are not sensitive to trial order, and, in particular, they cannot show highlighting (Daw, Courville, & Dayan, 2008; Kruschke, 2006b, 2006c).[1] These models' insensitivity to trial order is not a necessary shortcoming of all Bayesian models, however. These particular models ignore time (or trial) merely as a convenient mathematical simplification. Future Bayesian models might explicitly incorporate temporal dependencies.

Another approach is to try to explain highlighting as an inference during responding at test, rather than as an asymmetry during learning. The eliminative inference model (ELMO; Juslin, Wennerholm, & Winman, 2001; Winman, Wennerholm, & Juslin, 2003) is based on the idea that the test probe PE.PL is recognized to be an *un*known cue combination, and therefore known outcomes can be eliminated. If outcome E is well known, but outcome L is not, then E is eliminated and response L is preferred. Test probe I, on the other hand, is similar enough to learned rules that the known outcome E is evoked. There is good evidence that people do use some form of eliminative inference in some situations (Juslin et al.; Kruschke & Bradley, 1995). Unfortunately, it cannot account for highlighting. In particular, eliminative inference does not apply when all outcomes are well learned, but highlighting still occurs robustly in human preferences. Various details of response preferences are not captured by the ELMO model (Kruschke, 2001b, 2003a).

[1] The Kalman filter has a dynamic process that is sensitive to trial order, but the published versions of this mechanism do not account for highlighting (Daw et al., 2008; Kruschke, 2006b). And unlike the associative weights, the dynamic process parameters in the standard Kalman filter do not learn from training, but are fixed in advance. The rational model (Anderson, 1990, 1991) uses approximations that produce trial-order sensitivities, but these do not mimic highlighting (Kruschke, 2006b, 2006c).

The point of this section is merely to claim that the highlighting phenomenon is truly perplexing for many models of learning. There is not space here to thoroughly review all the contending models and the data that disconfirm them. The various references cited above provide many gory details of models impaled upon spikes of data.

2.2.1. Highlighting Is Explained by Attention Shifting

If all those theories do not explain highlighting, what does? A key insight was provided by Medin and Edelson (1988) (see also Medin & Bettger, 1991), who suggested that when learning I.PE → E, both cues are learned as moderately strong predictors of outcome E. Then, when learning I.PL → L, attention shifts away from cue I toward cue PL, and a strong link from PL to outcome L is acquired. Attention shifts away from cue I when learning I.PL → L because attention to cue I produces the wrong response, namely, outcome E.

A series of models that formalize attention shifting has been created by Kruschke (1996, 2001b, 2001c, 2006c) and extended to continuous stimuli by Kalish and Kruschke (2000; Kalish, 2001). The general framework of the models is displayed in Figure 1. Each cue has a multiplicative attentional gate, indicated in Figure 1 by triangles impinging upon the upward flow of cue activation. When attention on a cue is zero, then the cue activation is squelched. Each cue recruits some attention by its mere presence, but there can be competition for attention if there are multiple cues. A key aspect of the framework is that cue-outcome learning is actually indirect via two mappings: There is a learned mapping from cues to attentional allocation across the cues, and there is a learned mapping from attended cues to outcomes. These two distinct mappings are suggested by the curved arrows Figure 1.

The environment specifies which cues are present and which outcome is correct, but the environment does not specify how to allocate attention

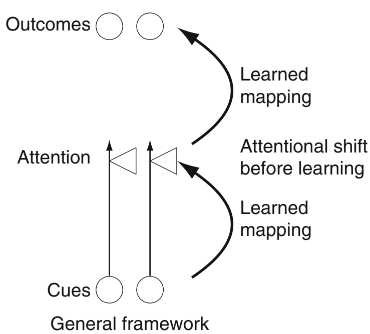

Figure 1 General framework for models of attentional shifting and learning.

across the cues. The models allocate attention to maximize the accuracy of the predicted outcome. In error driven, connectionist implementations of the framework (Kruschke, 1996, 2001b, 2001c), attention shifts away from cue I during the learning of I.PL → L because doing so reduces error. This attentional shift facilitates rapid acquisition of I.PL → L and reduces interference with the previously learned mapping I.PE → E. On a given trial, after attention has been shifted, then there is learning of the mappings from the presented cues to the attentional allocation, and from the attended cues to the outcomes. Attentional shifting and learning demonstrably improve performance on both early and late cases (Kruschke, 2003a).

In Bayesian implementations of the framework (Kruschke, 2006b, 2006c), attention shifts away from cue I during learning I.PL → L because doing so reduces inconsistency with the previously learned belief that cue I is associated with outcome E. After attention has been shifted on a given trial, the mappings are learned from the presented cues to the attentional allocation, and from the attended cues to the outcomes. In the Bayesian implementation, learning of a mapping entails shifting belief away from candidate mappings that are inconsistent with the training items, toward candidate mappings that are consistent with the training items (for an introduction to Bayesian associative learning, see Kruschke, 2008). Because of the attention shifting, this architecture for Bayesian learning robustly exhibits highlighting. An advantage of this Bayesian scheme over the connectionist models is that it can also exhibit phenomena known as "retrospective revaluation" (e.g., backward blocking, unovershadowing, etc.; see Kruschke, 2006c), which are very challenging to connectionist models but are naturally accommodated by Bayesian systems.

Because Bayesian learning of each mapping in Figure 1 is influenced only by its local information, the approach is called "locally" Bayesian learning. This learning scheme is different from standard Bayesian approaches in which both mappings are represented jointly in a global hypothesis space (e.g., Neal, 1996; Rumelhart, Durbin, Golden, & Chauvin, 1995). Globally Bayesian models do not exhibit highlighting because they are not sensitive to trial order. The locally Bayesian model is sensitive to trial order because the internal attentional targets, generated on a given trial to be least inconsistent with current beliefs, depend on previous learning.

Locally Bayesian learning is motivated generally by the idea that different levels of analysis may be Bayesian. Individual neurons might be Bayesian learners (e.g., Deneve, 2008), or committees of people might be Bayesian learners (cf. Akgün, Byrne, Lynn, & Keskin, 2007). Theories of mind typically posit numerous component processes, any of which could be Bayesian learners. For a mind to be globally Bayesian, it would have to keep track of all possible combinations of all possible states within and across components. This might be possible with clever algorithms, but it is more plausible to assume that each component keeps track of only its own possible states, and undergoes only locally Bayesian learning.

Another interesting behavior of locally Bayesian learning, when applied to highlighting, is that it learns faster than globally Bayesian learning (Kruschke, 2006c, p. 688). The retardation in the globally Bayesian system occurs because the global system must dilute its beliefs over a large number of possible joint hypotheses, and this uncertainty produces less decisive responses during learning.

In summary, the main point is that attention shifting is adaptive: Attention shifting accelerates acquisition of novel cases, and attention shifting preserves previous knowledge. The phenomenon of highlighting is a behavioral signature of this adaptive process. Highlighting is not an accidental deficiency in an otherwise well-tuned learning system. Highlighting is a direct consequence and sign of learning well.

2.3. Highlighting Is Robust, Pervasive, and Consequential

The claim, that highlighting is sign of learning well, is bolstered by the fact that it shows up in many places. It is not to be dismissed as a quirk, occurring by accident only in obscure and contrived conditions that have little relevance to most learning. The phenomenon is, in fact, robust and pervasive. And it has consequences predictable from attentional theory.

2.3.1. Robust

The effect persists under a variety of relative base rates, changes in base rates during training, different numbers of copies of the basic structure, different numbers of imperfect or perfect predictors, and so forth. For example, the designs of Medin and Edelson (1988) used three copies of the basic structure, but the designs of Medin and Bettger (1991) used four copies of the basic structure, and the designs of Kruschke (1996) used two copies. Robust highlighting was obtained in all the designs.

As another example, Medin and Edelson (1988, Experiment 2) reported a design in which one copy of the highlighting structure involved two shared predictors ($I_1.I_2.PE \rightarrow E$, $I_1.I_2.PL \rightarrow L$), a second copy had only one shared predictor but two perfect predictors for each outcome ($I.PE_1.PE_2 \rightarrow E$, $I.PL_1.PL_2 \rightarrow L$), and a third copy had no shared predictors ($PE_1.PE_2.PE_3 \rightarrow E$, $PL_1.PL_2.PL_3 \rightarrow L$). As anticipated by attentional theory, the magnitude of highlighting depended on the number of shared predictors. Kruschke (2001b, Experiment 1) also showed that a shared predictor was essential for producing highlighting, using a design with only two cues per outcome and only two copies of the basic structure.

Some researchers have used more extreme differential base rates than used in the original experiments by Medin and Edelson (1988). For example, Shanks (1992) and Juslin et al. (2001) used 7-to-1 base rates (instead of 3-to-1) and observed highlighting. The more extreme base-rate ratio could produce a stronger highlighting effect, presumably because it more strongly ensured that one outcome is well learned before the other outcome is learned.

Medin and Bettger (1991) explored changes in relative base rates during training. As long as one outcome had higher base rate than the other during initial training, thereby causing the high base-rate case to be learned before the low base-rate case, then the highlighting effect was observed. Subsequent designs have used only two copies of the basic structure, both changing base rates at the same time, and again found strong highlighting (Kruschke, 2001b; Kruschke, Kappenman, & Hetrick, 2005).

Across all these variations in design, the essential features seem to be that (i) one outcome is learned before the other outcome, (ii) the shared cue is associated with the early outcome, and (iii) the later learned outcome is well learned by test time. These design aspects are distilled into a "canonical" design described later in this chapter. An emphasis of the canonical design will be that highlighting does not depend on differential base rates overall; instead, the essential requirement is that one outcome is well learned before the other outcome is learned.

Various experiments have used different stimuli or cover stories or procedures. For example, in unpublished research conducted in 2001 by Kruschke with collaboration of an undergraduate honors student named Nancy Aleman, participants were instructed that they were to learn about the qualities of whitewater rafts. This knowledge could be used for decisions about which rafts to rent or purchase. Learners browsed 20 Web pages to learn about the rafts currently available on the market. Figure 2 shows an example of a Web page seen by the learners. Two features of the raft are given prominence in the display, along with the quality rating. The instance in Figure 2 features "Lateral Valves" and "Hexagonal Aircells," with a "High" quality rating. These attributes might correspond to abstract cue I, cue PE, and outcome E, respectively. Additional text reiterates the features and quality in prose that was intended to imitate catalog sales descriptions. Notice that the pages did not require any explicit quality prediction for each case; learners merely read the information on the page. Participants selected whatever page they wanted to inspect next by selecting it from among the array of raft names at the bottom of the page. If a participant systematically selected rafts in reading order, that is, left to right and top to bottom, then they would encounter I.PE $\rightarrow$ E cases before I.PL $\rightarrow$ L cases. Most subjects did spontaneously select rafts in that order. Across all 20 pages, there were an equal number of E and L cases. After viewing all 20 pages, learners then viewed a few pages that purported to show prototypes of rafts that manufacturers were considering bringing to market. Participants predicted the quality of each raft based on the features of the raft. Results showed a strong highlighting effect in predicted quality: Rafts with the imperfectly predictive feature were given the earlier learned quality, and rafts with a combination of the two

Figure 2 Example of stimulus used for assaying highlighting in browsing a catalogue of whitewater rafts.

perfectly predictive features were given the later learned quality. These results show that overt predictive learning is not necessary for highlighting, nor is an austere "cues only" display.

Pictorial stimuli with joystick responses were used by Fagot, Kruschke, Dépy, and Vauclair (1998). Simple geometric figures, such as an oval or rectangle, were used to instantiate cues. The learner initiated a trial by using a joystick to move the cursor to the center of the screen. The cue figures would appear on the left or right of the screen. The learner made a response by moving the cursor to one of two colored squares that were positioned vertically above or below the start box. Learners were told merely to figure out which box to move to, in response to the various figures. The results again showed robust highlighting. Lamberts and Kent (2007, described in more detail below) also used pictorial stimuli and found robust highlighting. Although the stimuli might have been covertly named by the learners, these results show that textual stimuli are not necessary for highlighting to occur.

The effect has been found with socially relevant stimuli such as personality traits and group membership (Sherman et al., 2009; Wedell & Kruschke, 2001). In one design, Wedell and Kruschke (2001) trained people to predict a (fictitious) person's identity from his personality attributes. For example, the abstract case I.PE → E was instantiated as "honest" and "conventional" indicates "Fred," and the abstract case I.PL → L was instantiated as "honest" and "materialistic" indicates "Jack." The shared trait, "honest," is known from previous norms to be a positive trait, while the distinctive traits, "conventional" and "materialistic," are known to be equally negative traits. After learning to predict the person names from the traits, participants were asked to rate the likeability of each person. Presumably the rating of likeability is based on how strongly the traits have been associated with each person. If the traits were asymmetrically highlighted during learning, then the later learned person should be more strongly associated with the distinctive negative trait, and the earlier learned person should be more strongly associated with the shared positive trait. The actual likeability ratings confirmed this prediction, with the early learned person being rated more likable than the later learned person. Notice that ratings of likability use associations from outcomes (the person name) to cues (the traits), rather than from cues to outcomes, which suggests that the highlighting effect is caused by asymmetries in associations, not purely by biases at test.

The highlighting effect is modulated by cue salience, as anticipated by attentional theory. Continuing from the previous paragraph with the example of trait-name learning, Wedell and Kruschke (2001) found that if both the PE and PL traits were equally negative or equally positive, then a typical magnitude of highlighting was obtained. Previous literature strongly suggests that negative traits are more salient than positive traits. In other words, negative traits should attract attention more than positive traits. Consistent with this prediction, Wedell and Kruschke (2001) found that highlighting was magnified when the PL trait was negative while the PE trait was positive, and highlighting was diminished when the PL trait was positive while the PE trait was negative. Analogously, Bohil, Markman, and Maddox (2005) found that a highlighting-like effect could be generated if one distinctive cue were more salient than the other distinctive cue, even when the two outcomes were learned contemporaneously.

In a cued-recall paradigm, effects exactly analogous to highlighting were obtained by Dennis and Kruschke (1998). Learners saw two words such as "digit" and "album" at the top of a computer screen for 2 s, and were instructed to covertly anticipate the word, such as "shark," that would appear after a pause at the bottom of the screen. Learners simply watched a sequence of such trials before a test phase in which words appeared at the top of the screen and the anticipated word had to be typed on the computer keyboard. This procedure is interestingly different from the standard predictive-learning paradigm. First, there is no explicit feedback regarding the correctness of the covertly anticipated response during learning. Second, there is no cover story relating the cues to the outcomes, and no causal relationship such as that between diseases and symptoms (used in previous research by Kruschke, 1996; Medin & Bettger, 1991; Medin & Edelson, 1988). Third, and perhaps most importantly, the response in the test phase is not limited to the words seen as outcomes during learning, because participants could type in any word at all, including the cue words or any other word that came to mind. Despite these differences, the test results were remarkably consistent with the results from previous predictive-learning experiments, revealing robust highlighting. Thus, forced choice at test is not required for highlighting to occur.

The highlighting effect is also robust under time pressure and a dual task during test. After training with pictorial stimuli in a design using fixed 3-to-1 base rates, Lamberts and Kent (2007) tested participants in four different conditions. One test condition allowed the usual unpressured response. A dual-task condition had subjects simultaneously counting quickly backward in multiples of three during the test responses. Two other conditions demanded responses be given within 500 or 300 ms. The signature torsion of highlighting was clearly obtained in all four test conditions, merely somewhat attenuated in the speeded conditions. Lamberts and Kent (2007) argued that the robustness of highlighting under time pressure and a dual task made it unlikely that highlighting can be fully explained by inferential rules executed at time of test, because rule application should be disrupted by those additional cognitive demands.

2.3.2. Highlighting Is Correlated with Blocking and Gaze

Learning in other cue-outcome designs should also be affected by attentional shifting. One such design, known as "blocking" (Kamin, 1968; Shanks, 1985), trains people in an early phase with cases of A → 1, then in a later phase with cases of A.B → 1. In other words, the later phase introduces a perfectly predictive cue which is redundant with an already learned cue. As a comparison, the later phase also has cases of C.D → 2, without any earlier training of cues C or D. In test, the redundant cue is put in conflict with a comparison cue: B.D → ? People prefer outcome 2, which suggests that learning about cue B was attenuated, or "blocked," because of the previous learning about cue A.

One explanation of blocking is that it is caused, at least in part, by learned *in*attention to the blocked cue (e.g., Kruschke & Blair, 2000; Mackintosh & Turner, 1971). The idea is that during learning of A.B → 1, cue B distracts attention away from the already predictive cue A. This distraction causes diminished accuracy. To alleviate the error, attention is redirected back to cue A, away from cue B. Thus, people learn to suppress attention to cue B.

Because the same attentional shifting process is supposed to be at work in both blocking and highlighting (but yielding complementary effects), the effects should be correlated. In other words, a person who has especially strong attentional shifting should show relatively strong blocking and highlighting, but a person who has relatively small attentional shifting should show a lesser degree of blocking and highlighting.

This predicted correlation was verified by Kruschke et al. (2005). People were trained on both blocking and highlighting designs, and magnitudes of blocking and highlighting were estimated for each person from their choice preferences at test. Across people, there was a significant positive correlation between blocking and highlighting.

The correlation of blocking and highlighting is another challenge to models of the phenomena. The attentional shifting and learning model of Kruschke (2001c) was shown to accommodate the correlation (Kruschke et al., 2005). Specifically, when the attentional parameters of the model are varied, to mimic individual differences in attentional shifting, the model naturally predicts covarying magnitudes of both blocking and highlighting. Importantly, variations in other parameters, such as associative learning rates or choice decisiveness, do not account for the covariation. Other models have difficulty addressing this correlation.

Attentional theory asserts that covert attention is directed at the highlighted cue. If overt eye gaze reflects covert attention, then gaze should dwell for longer duration on highlighted cues and for shorter duration on blocked cues. This prediction was confirmed by Kruschke et al. (2005). Figure 3 shows an example of a gaze trajectory on a single trial, where the clusters of dots indicate places where the eyes fixated. Moreover, individual measures of differential gaze durations correlated with differential choice preferences. In other words, people who showed stronger blocking and highlighting in their choice preferences tended to show greater differences in gaze durations for blocked or highlighted cues. The correlations between choice preferences and gaze differences, and between blocking and highlighting, are shown in the lower part of Figure 3. Although the correlation of choice and gaze is not a necessary prediction of attentional theory, because it is based on the additional assumption that overt gaze follows covert attention, the correlation of blocking and highlighting is a fairly firm prediction, qualified only by the independent variation induced by other influences.

2.3.3. Learning *After* Highlighting

Attentional theory posits that learners rapidly reallocate attention across cues when the default allocation causes inaccurate prediction. This idea is annotated in Figure 1 as ‘‘Attentional shift before learning.’’ A further premise is that people learn these reallocations of attention, so that on subsequent repetitions of the same cues, attention can be more appropriately apportioned and yield more accurate responses. This idea is annotated in Figure 1 as ‘‘Learned mapping’’ from cues to attention.

If attentional allocations are learned in highlighting and blocking, then the learned allocations should take time to overcome if the cue-outcome

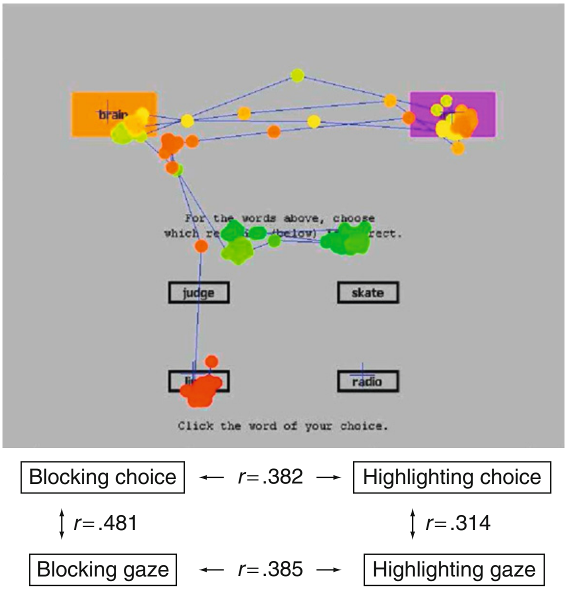

Figure 3 Top: Example of a gaze trajectory in experiment by Kruschke, Kappenman, and Hetrick (2005). Each dot indicates gaze location as sampled at 1/60 s, with lines connecting consecutive locations. The trajectory begins with the dots near the center over the instructions, moves up to the dots over the cue words at the top of the display, and then moves down to the dots over the response button that was clicked with the screen cursor. Bottom: Correlations, across individuals, of magnitude of blocking or highlighting, assayed by choice or gaze preference.

mapping changes in subsequent training. Specifically, if people have learned to ignore a blocked cue, then learning a new association from the blocked cue should be relatively difficult in subsequent training. This prediction was confirmed in different experiments reported Kruschke and Blair (2000) and Kruschke (2005).

Moreover, if people have learned to attentionally highlight cue PL in the highlighting design, then it should be difficult to ignore the highlighted cue if it becomes irrelevant in subsequent training. This prediction was also confirmed by Kruschke (2005). The experiment trained people in a typical highlighting design and then continued training with new outcomes. For both of two groups of learners, the new outcomes were perfectly indicated by the cues that had been the imperfect I cues during highlighting. For one group of learners, the I cues were accompanied by the PE cues, which were randomly paired with the novel outcomes, but for the other group of learners, the I cues were accompanied by the PL cues, again randomly paired with the novel outcomes. If there was stronger learned attention to the PL cues than to the PE cues, then learning to ignore the newly irrelevant

PL cues should be more difficult than learning to ignore the newly irrelevant PE cues. This difference in learning difficulty was in fact observed in the data.

2.3.4. Highlighting with Continuous Cues and Outcomes

The previous sections discussed experiments in which the cues were present/absent features, such as words or geometric figures. In the real world, cues can instead have continuous magnitudes, not just binary discrete states. In recognition of these alternative cue instantiations, some researchers have sought effects analogous to highlighting with continuous cues, and even continuous outcomes.

Kalish and Kruschke (2000) considered continuous-dimension stimuli with categorical outcomes. The cue-outcome structure was not intended as a direct analogue of highlighting, but was intended to examine shifts of attention among values within a dimension. The hypothesis was that early learned stimuli would be encoded in terms of their typical, average values. Later learned stimuli, of different categories, would be encoded by more extreme stimulus values, because those extreme values would help discriminate the new category from the previously learned one. A model was developed that incorporated attentional shifts across dimensions, but also attentional shifts across values within dimensions. The model was able to mimic some subtle effects in people's choice preferences across the continuum of stimulus values, but those subtleties could not be captured when the attention shifting in the model was disabled.

Kalish (2001) considered a design directly analogous to highlighting, in which the present/absent values of the standard experiment were instantiated as two different values on a continuum; such as short and tall heights of a vertical bar. In different experiments, the heights had different amounts of random noise added. When the random variation did not cause categories to overlap in stimulus space (i.e., when there was a deterministic mapping from stimuli to outcomes), highlighting was obtained. Kalish modeled the results with an extension of the attention-shifting model presented by Kalish and Kruschke (2000).

When both the cues and outcomes are continuously valued, the design falls into the realm of "function" learning. This appellation in the literature is apparently based on analogy to high-school mathematics, wherein mappings from continuous x to continuous y, such as lines and higher order polynomials, are the prototypical functions. If function learning and discrete-outcome learning are related, it is plausible that attentional shifts should occur during function learning. Suppose, for example, that cues I, PE, and PL are instantiated as continuous valued dimensions, such as body temperature, grade point average, and hair length. People are trained early with cases in which small values of I and PE lead to small values of the outcome, and other cases in which large values of I and PE lead to large values of the outcome. Thus, the I and PE values covary across trials and indicate correspondingly covarying outcome values. Later in training, people are trained with cases in which values of I and PL covary, but the outcome is *negatively* correlated with the cue values. In other words, the function relating I.PE cases to the outcome is positive linear, but the function relating I.PL cases to the outcome is negative linear. If attentional highlighting occurs, then, when tested with cue I by itself, people should prefer to give positive linear responses, but, when tested with cues PE.PL, people should prefer to give negative linear responses. This pattern of responding was in fact observed in an experiment reported by Kruschke (2001a). The analogous result for blocking was also found.

In summary, highlighting does not seem to be limited to discrete cues and outcomes. Although there has been relatively little investigation of highlighting with continuous cues, it seems advisable that theories of highlighting should be extendible, in principle at least, to continuous cues and outcomes.

2.3.5. Possible Sightings Afield

A variety of phenomena in other domains have been addressed by attentional theories much like the one that accounts for highlighting. These phenomena tend to share two main qualities. First, learning of new items can be fast. This rapidity can be explained, at least in part, by the ability of attention to focus on distinctive features or representations that reduce interference with previously learned items. Second, learned knowledge can be distorted relative to the actual stimulus statistics. This distortion also can be explained, at least in part, as the consequence of selective attention that is differently tuned for different items at different points of learning. These ideas have been applied to aspects of *language acquisition* (Colunga & Smith, 2008; Ellis, 2006; Goldberg, Casenhiser, & Sethuraman, 2005; Parish-Morris, Hennon, Hirsh-Pasek, Golinkoff, & Tager-Flusberg, 2007; Regier, 2005; Smith & Yu, 2008; Yoshida & Hanania, 2007), *consumer learning* (Cunha, Janiszewski, & Laran, 2008; Cunha & Laran, 2009; Kruschke, 2006a; Pieters, Warlop, & Wedel, 2002; van Osselaer & Janiszewski, 2001), *context cues* in learning (Nelson & Callejas-Aguilera, 2007; Rosas & Callejas-Aguilera, 2006; Rosas, Callejas-Aguilera, Ramos-Álvarez, & Abad, 2006), and learning in *social cognition* (e.g., Cramer et al., 2002; Hayes, Foster, & Gadd, 2003; Sherman et al., 2009; Wedell & Kruschke, 2001), among others. There is not space here to discuss all these connections to the literature, but it is hoped that these pointers are suggestive of the potential scope of highlighting in learning.

2.4. Interim Summary and Goal of Remainder

In summary, the highlighting effect has been found with a variety of stimuli, cover stories, stimulus frequencies, and cue combinations. It is correlated with blocking, and it has predictable consequences for subsequent learning. Highlighting is not merely a stubborn deficiency of otherwise rational learning; rather, highlighting is adaptive because it reduces interference with previous knowledge and accelerates acquisition of new knowledge. The style of attentional theory that explains highlighting has been applied in a variety of domains. Thus, the highlighting phenomenon is among the catalog of major phenomena that learning theories need to address. Other researchers agree: "Because [highlighting] is so problematic, we will argue that the effect goes to the heart of several important issues in human learning and decision making" (Johansen, Fouquet, & Shanks, 2007, p. 1366).

The primary goal for the remainder of this chapter is to present new results from a "canonical" highlighting experiment that may serve as a test bed for models of learning. In a canonical design, the overall frequencies of the early and late cases are equal. In other words, there is no overall difference in base rates. The canonical design also has an initial phase in which the early cases are trained without any interspersed late cases, thereby guaranteeing that the early cases are actually learned before the late cases. One purpose of this canonical design is to demonstrate unambiguously that the highlighting effect does not depend on overall differences in bases rates; that is, the highlighting effect is not (only) an inverse base-rate effect, because there are no overall base rate differences to invert. Another purpose of the canonical design is provide concrete data that challenge models that rely on differential base rates to account for the highlighting effect. Such models include some recent Bayesian approaches, including the Rational model (Anderson, 1990, 1991) and the Kalman filter model (Dayan et al., 2000; Kruschke, 2008). Finally, the data are analyzed using Bayesian methods, unlike all previous reports in the literature. The hierarchical Bayesian analysis allows for individual differences, and it provides a complete posterior distribution of credible response preferences.

3. Experiment: A "Canonical" Design with Equal Base Rates

A framework for a "canonical" design for highlighting was suggested by Kruschke (2006c, Table 1, p. 686). The design is guided by three motivations. First, some exposures to I.PE → E should occur initially, so that it is definitely learned first. Second, the total number of cases of I.PE → E should equal the total number of cases of I.PL → L. Third, aside from the

Table 1 A Canonical Highlighting Design.

Phase	# blocks	Item × Frequency	
First	N_1	I.PE → E × 2	
Second	N_2	I.PE → E × 3	I.PL → L × 1
Third	$N_3 = N_2 + N_1$	I.PE → E × 1	I.PL → L × 3
Test	2	I.PE → E × 2	I.PL → L × 2
		I → ? × 1	PE.PL → ? × 1, etc.

Note: An item is shown in the format, Cues → Correct Response × frequency per block. The actual experiment has two copies of the structure shown here; for example, the first phase involves I1.PE1 → E1 × 2 and I2.PE2 → E2 × 2.

initial training, the relative base rates should never be too extreme, because people should be learning about the cases in relation to each other. The 3-to-1 base rates established by Medin and Edelson (1988) and by Medin and Bettger (1991) were used as a guideline.

Table 1 shows a canonical highlighting design. It has three phases of training. The first phase presents only cases of I.PE → E, to ensure that at least some learning of the early cases does happen before the later cases. A block of the first phase involves two repetitions of I.PE → E, and there are N_1 blocks. The second phase introduces the cases of I.PL → L, but at only one third the frequency of the early cases. There are N_2 blocks of the second phase. The third phase reverses the base rates, emphasizing the later learned cases. The third phase has N_3 blocks. Within all blocks, the trials are permuted randomly. The blocks progress seamlessly without any marker between blocks.

Notice in the table that when $N_3 = N_2 + N_1$, the total number of I.PE → E trials is $3\ N_1 + 4\ N_2$, which equals the total number of I.PL → L trials. This equality of base rates distinguishes highlighting from the inverse base rate effect reported by Medin and Edelson (1988), which used only the second phase of Table 1, i.e., $N_1 = 0$ and $N_3 = 0$. One possible infelicity of the canonical design proposed here is that training ends with one outcome occurring more often than the other, and this short-term imbalance in favor of the later trained outcome may carry over into the test items. To solve this problem, a fourth training phase could be appended (still before the test phase) in which the two cases are interspersed with equal frequency. Such a candidate fourth phase was not used here for two reasons. First, the test phase includes continued interspersed training with equal base rates, as shown Table 1, albeit with only a modest number of repetitions. Second, Medin and Bettger (1991, Experiment 2) showed that training with equal base rates after an initial phase with 3-to-1 base rates still produced the signature torsion of highlighting.

Medin and Bettger (1991) reported experiments in which one subset of the cue-outcome pairs had balanced frequencies, corresponding with $N_1 = 0$, $N_2 = 6$, and $N_3 = 6$. The canonical design instead has $N_1 > 0$ to assure that the early items really are learned before the later items. The designs used by Medin and Bettger (1991) also interleaved learning of balanced structures with imbalanced structures, leaving open the possibility that learning of an imbalanced structure influenced the learning of a balanced structure.

The canonical design does not require the number of blocks to be fixed in advance. Instead, training can continue in the first and second phases until an accuracy criterion is reached. For example, training in phase 1 could continue until accuracy achieves 11/12 in a window of three consecutive blocks (as was done by Kruschke, Kappenman, & Hetrick, 2005), and training in phase 2 could continue until accuracy on the later items achieves 5/6 in a window of three consecutive blocks. With the number of blocks in the first two phases, N_1 and N_2, established by the subject's achievement of criterial accuracy, the number of blocks for the third phase is set as $N_3 = N_1 + N_2$, thereby achieving overall balance of base rates while also assuring early learning of one case and high accuracy overall. Moreover, by using an accuracy criterion, the framework of the design can be applied to different stimuli, situations, and subjects, in which or for whom learning may be more or less difficult. The experiment reported below, however, used a fixed number of blocks, merely to maintain consistency with previously reported experiments.

The equality of base rates in the canonical design emphasizes that highlighting is an order-of-learning effect, not a base rate effect. It is only by virtue of the fact that the I.PE cases are learned before the I.PL cases that asymmetric responding occurs at all. If the I.PE and I.PL cases were intermixed equally throughout training, they would be structurally equivalent and no such highlighting effect could be meaningfully assayed (except for idiosyncratic differences in acquisition order by individual subjects).

3.1. Method

3.1.1. Design

The canonical design of Table 1 was used with $N_1 = 10$ and $N_2 = 5$. There were two copies of the basic design intermixed, so that the first phase involved more than one correct response. Hence there were a total of six cues and four outcomes. This yielded a total of 200 training trials. Across the 200 training trials, there were 50 trials of each of the I1.PE1 → E1, I1.PL1 → L1, I2.PE2 → E2, and I2.PL2 → L2 items. The order of items was randomly permuted within each block.

The testing phase continued seamlessly after the training phase. Each testing block contained two trials of each of the four training items with feedback, as indicated in Table 1. This continued training equalized the short-term base rates during test, served as a reminder of the correct outcomes in the midst of the test trials, and simultaneously assessed accuracy on the training items. Each testing block also contained the 11 other test types shown in Table 2. Each of the 11 test types was probed once per block for each copy of the cue structure. Therefore each test block contained 30 trials, which were randomly permuted within blocks. There were two test blocks. The totality of the experiment comprised 260 trials, and took approximately 15 min for a participant to complete.

3.1.2. Stimuli

The six cues words were either the set, "snake," "robin," "whale," "puppy," "skunk," and "trout," or else the set, "child," "mouse," "ocean," "tulip," "piano," and "arrow." These words were selected because they are highly concrete and imagable, they all have five letters, they all have different initial letters (within a set) that are also different from the letters of the response keys, and there are no striking semantic relationships between words (within a set). The set used for a participant was selected randomly. The assignment of the six words to the six abstract cue types was randomly permuted for each participant.

The response keys were F, G, H, and J. These are the four central keys on a standard keyboard. Figure 4 shows examples of the stimuli as displayed

Table 2 Response Percentages for Each Probe in the Test Phase of the Canonical Highlighting Design.

	Response			
Cues	E	L	Eo	Lo
I.PE	91.8	5.9	1.0	1.4
I.PL	3.9	93.9	1.4	0.8
I	63.7	26.2	6.2	3.9
PE.PL	35.2	57.8	3.5	3.5
PE.PLo	29.3	5.9	5.1	59.8
PE	85.9	5.1	5.1	3.9
PL	3.9	87.5	5.5	3.1
I.PE.PL	43.8	45.7	3.5	7.0
I.PEo.PL	13.3	62.5	17.6	6.6
I.PE.PLo	48.4	7.8	5.5	38.3
I.PEo.PLo	9.8	16.0	27.7	46.5
I.PEo	21.9	19.9	51.6	6.6
I.PLo	11.7	16.8	3.1	68.4

Note: The first two rows are based on 8 trials/subject, and the remaining rows are based on 4 trials/subject, with 64 subjects.

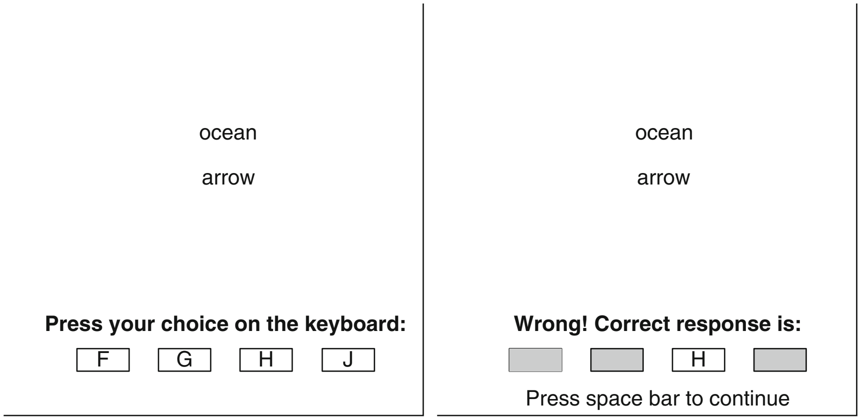

Figure 4 Left: Computer display for cues with response prompt. Right: Computer display for cues with corrective feedback. The actual displays had gray backgrounds, rendered here as white.

on the computer screen. The assignment of keys to abstract labels (E1, L1, E2, and L2) was randomly permuted for each participant.

Figure 4 shows examples of the stimuli and feedback as actually presented on the computer screen. The position of the cue words was randomly permuted from trial to trial. For example, on some I.PL → L trials, cue I appeared above cue PL, but on other trials, cue PL appeared above cue I.

3.1.3. Instructions

The instructions to the participant provided no causal cover story. For example, there was no mention of symptoms and diseases that several previous studies used (e.g., Kruschke, 1996; Medin & Bettger, 1991; Medin & Edelson, 1988). The instructions were neutral, saying only the following:

In this experiment you will see some common words on the computer screen. Your job is to learn which words indicate which keys to press. You can press "F," "G," "H," or "J." When the words are presented, you make a guess by pressing one of the keys. Please locate the F, G, H, and J keys on the keyboard now—they are in the middle of the keyboard. After you make your choice in response to the words, the correct answer will be displayed. At first you will just be guessing, but after several repetitions you can learn which words indicate which keys. The correct keys for the words never change, so you can achieve perfect accuracy if you try. At some times during the experiment, new words may be introduced. Just learn these new words as accurately as you can.

3.1.4. Participants

Participants volunteered for partial credit in introductory psychology courses at Indiana University. This subject pool has a median age of approximately 19 years and is about 50–60% female. Procedures for protection of human subjects were approved by the local Institutional Review Board. There were 72 participants.

3.2. Results

3.2.1. Learning Criterion

The results on the generalization probes are only of interest if the participants accurately learned the training items. If chance performance is considered to be 1/4 correct, because there were four response options, then significantly above chance requires 6 out of 8 correct (two-tailed, $p < 0.05$).[2] Therefore, if a participant showed fewer than 6 out of 8 correct responses on either I.PE or I.PL trials in the test phase, he or she was excluded from further analysis. The learning criterion eliminated only 8 of 72 participants (i.e., 11%), leaving $N = 64$.

3.2.2. Choice Data

Table 2 shows the average percentage of choices of each response category, for all the different test items. Each cue had outcomes with which it was associated during training, and *other* outcomes with which it was not associated. For example, during training, there occurred cases of I1.PL1 → L1 and I2.PL2 → L2. In test, there were probes involving combinations of cues from different sets, such as I1.PL2 and I2.PL1. Because of the structural symmetry in the design, these cases were collapsed and denoted I.PLo, with the lowercase "o" indicating the *other* copy of the cues. Responses corresponding with the other cue were also marked with an affixed lowercase "o." For example, if the probe is I1.PL2 and the response is L2, the probe is tabulated as a case of I.PLo with response Lo. If the response to I1.PL2 is instead E1, it is tabulated as a case of response E.

First, notice that accuracy for the training items was very high in the test phase. (Recall the learning criterion demanded 6 out of 8, i.e., 75% correct, on both items.) The first two rows of Table 2 indicate that performance on the training items was in the low-nineties percent correct.

[2] The learning criterion can be motivated from a Bayesian perspective instead of from null hypothesis significance testing. Suppose the prior belief regarding the underlying probability correct on training items has a mean of 1/4, that is, guessing, but has a large uncertainty, expressed as a beta(1, 3) distribution. When 6 of 8 test trials are correct, the resulting posterior beta(6 + 1, 2 + 3) distribution has a 95% HPD interval (from 0.318 to 0.841) that excludes the chance value 0.25. But when only 5 of 8 test trials are correct, the posterior beta(5 + 1, 3 + 3) distribution has a 95% HPD interval (from 0.234 to 0.766) that includes the chance value 0.25. The same conclusion is reached if the prior is beta(2, 6), instead of beta(1, 3), which expresses somewhat higher prior certainty that the learner is merely guessing.

The results show a robust highlighting effect. For the imperfect cue I (third row of Table 2), there was a strong preference for response E over response L, with people selecting E more than twice as often as L (63.7 vs 26.2%). Statistical analyses are provided in Section 3.2.3. On the other hand, for the conflicting-cue case of PE.PL (fourth row of Table 2), there was a robust preference for response L over response E. Thus, the trademark ''torsion'' of highlighting is strongly displayed in this canonical design.

The dominance of PL over PE is also revealed by several other test probes. Probe PE.PLo (fifth row of Table 2) shows that response Lo is preferred over response E. Probe I.PEo.PLo (third from bottom row of Table 2) shows that Lo is preferred over Eo. And comparing I.PEo with I.PLo (bottom two rows of Table 2) shows that PLo dominates I more than PEo dominates I.

The remaining probes are included primarily to fill out all possible cue combinations (with up to three cues), for thoroughness and as additional constraints for future model fitting.

3.2.3. Bayesian Statistical Analysis

The data were analyzed using Bayesian methods. The appendix provides a few general reasons to prefer Bayesian methods over traditional null hypothesis significance testing. For the specific application here, traditional chi-square tests, which have been used in previous reports, are problematic because it is unclear how to combine data across subjects. Previous analyses have made the implausible assumption that all subjects are equally representative of a mutual übersubject, without any allowance for individual differences. Moreover, the traditional chi-square analyses merely test a null hypothesis of equal responding, without providing an estimate of what range of response biases are tenable, given the data. Both of these problems are addressed by the Bayesian analysis.

In the Bayesian analysis, a descriptive model of the data is defined, and the parameter values of the model are estimated. The Bayesian analysis yields a degree of belief in all possible parameter values, not merely a single best-fitting parameter value. In the following paragraphs, the model is first defined, followed by a description of how the posterior distribution was generated, followed, finally, by a description of the posterior distribution itself.

The left side of Figure 5 suggests the basic structure of the model, informally. At the bottom left of the diagram, each individual's observed response frequencies are a random sample from that individual's underlying response propensity. The downward arrow in Figure 5 represents the generation of responses based on underlying propensities. Moving up a level, each individual's underlying response propensity is considered to be a random draw from some overall distribution of response propensities,

Informal	Formal notation
Overall response propensity	$\vec{\alpha} = \langle \alpha_E, \alpha_L, \alpha_{Eo}, \alpha_{Lo} \rangle$
$\cdots\downarrow\cdots$	$\cdots\downarrow\cdots$ $\vec{\pi}_i \sim \text{dirichlet}(\vec{\alpha})$
Individual response propensity	$\vec{\pi}_i = \langle \pi_{E,i}, \pi_{L,i}, \pi_{Eo,i}, \pi_{Lo,i} \rangle$
$\downarrow$	$\downarrow$ $\vec{y}_i \sim \text{multinomial}(\vec{\pi}_i)$
Individual response frequency	$\vec{y}_i = \langle y_{E,i}, y_{L,i}, y_{Eo,i}, y_{Lo,i} \rangle$

Figure 5 Hierarchical model analyzing each test item. Not indicated in the diagram is the hyperprior on α, which was $\alpha_r \sim$ gamma (0.25, 0.0025) *r*. See main text for discussion.

governed by the cue combination. In other words, the cue combination at test evokes some overall response propensity. That overall response propensity has somewhat different manifestations in different individuals. The variation across individuals, due to distinct draws from the overarching propensity, is represented by the downward arrow with ellipses on either side.

The informal structure on the left side of Figure 5 is given formal precision on the right side of the figure. Notation will be explained from the bottom up. Recall that in the test phase, each cue combination was presented to the learner several times. For example, the test cue I was presented to each learner four times, and the four responses might comprise 2 E's, 1 L, 1 Eo, and 0 Lo's. These response frequencies, for the *i*th individual, are denoted by $\vec{\gamma}_i = \langle \gamma_{E,i}, \gamma_{L,i}, \gamma_{Eo,i}, \gamma_{Lo,i} \rangle$, on the lowest row in Figure 5.

The particular response frequencies are modeled as a random sample from the individual's underlying response propensities, denoted $\vec{\pi}_i = \langle \pi_{E,i}, \pi_{L,i}, \pi_{Eo,i}, \pi_{Lo,i} \rangle$ in Figure 5. Mathematically, a random sample of categorical responses is generated by a multinomial distribution with underlying probabilities $\pi_{E,i}$, $\pi_{L,i}$, $\pi_{Eo,i}$, and $\pi_{Lo,i}$ (which sum to 1), and this sampling is denoted $\vec{\gamma}_i \sim \text{multinomial}(\vec{\pi}_i)$.

An individual's response propensities are assumed to be a random representative of the overall response propensity induced by the test item. The overall response propensity for a test item is denoted $\vec{\alpha} = \langle \alpha_E, \alpha_L, \alpha_{Eo}, \alpha_{Lo} \rangle$ in the top row of Figure 5. Mathematically, a random sample of response probabilities is generated from a Dirichlet distribution that has parameters α_E, α_L, α_{Eo}, and α_{Lo}.

In summary, this hierarchical model allows individual differences to be captured by participant-level multinomial probabilities, mutually constrained by being drawn from the same higher level Dirichlet distribution which describes across-subject response tendencies for the cues.

The primary goal of the analysis is to generate a posterior estimate of overall response propensities $\vec{\alpha}$ for each probe item. For example, suppose that the estimated posterior distribution on the $\vec{\alpha}$ parameters for test cue I has a typical value of $\langle \alpha_E, \alpha_L, \alpha_{Eo}, \alpha_{Lo} \rangle = \langle 300, 500, 100, 100 \rangle$. This implies that typical individual-level response probabilities will be near $\pi_{E,i} = \alpha_E / \Sigma\alpha_k = 0.30$, $\pi_{L,i} = \alpha_L / \Sigma\alpha_k = 0.50$, $\pi_{Eo,i} = \alpha_{Eo} / \Sigma\alpha_k = 0.10$, and $\pi_{Lo,i} = \alpha_{Lo} / \Sigma\alpha_k = 0.10$. The posterior distribution on the α parameters yields the explicit posterior probability that, for example, the response tendency for L is greater than the response tendency for E. This will be explained in more detail below, with the actual posterior distributions of specific probe items.

The posterior on the α parameters is also indicative of the across-subject consistency of responses. If all subjects give the same distribution of responses to a cue, then the α estimates are high, because high α's yield little variation among individual π_i values. But if subjects give responses that vary a lot from one person to another, then the posterior α values are low, to allow for variation among individual π_i values.

The prior distribution on the α parameters was set to be vague and equal for all components. Specifically, the prior on each α was a gamma density with mean 100 and standard deviation 200 (yielding gamma parameters of shape = 0.25 and rate = 0.0025). Because very small values of α caused trouble for the Dirichlet sampling, the gamma distributions were censored at 0.3. Small changes in the arbitrary censoring value yielded trivial changes in the posterior. This vague and unbiased prior was selected in an attempt to be unobjectionable to a general skeptical audience. (If the prior were instead informed by previously published results from related designs, such as those of Medin and Bettger (1991), then the posterior distributions reported below would be even stronger.)

The posterior distribution was determined by Markov chain Monte Carlo (MCMC) approximation. The simulations used the software BRugs, which is an R-language interface to OpenBUGS, which in turn is based on WinBUGS (Lunn, Thomas, Best, & Spiegelhalter, 2000). Five parallel MCMC chains were simulated, using a burn-in of 50,000 steps and thinning of 1000 steps. This extensive burn-in and thinning produced well-mixed chains with small auto-correlation, so the posterior sample is very trustworthy. From each of the five chains, 1000 steps were retained to represent the posterior, yielding 5000 representative parameter values.

Figure 6 shows results for selected cues. The upper panel shows results from cue I. The Bayesian analysis yielded 5000 representative points $\langle \alpha_E, \alpha_L, \alpha_{Eo}, \alpha_{Lo} \rangle$ in the posterior distribution. Each of those points indicates a credible combination of α values, given the data. At any of the 5000 points, the estimated overall probability that participants give a response of E is $p(E|I) = \alpha_E/(\alpha_E + \alpha_L + \alpha_{Eo} + \alpha_{Lo})$. The preference of response E compared to response L is, therefore, $p(E|I) - p(L|I) = (\alpha_E - \alpha_L)/(\alpha_E + \alpha_L + \alpha_{Eo} + \alpha_{Lo})$.

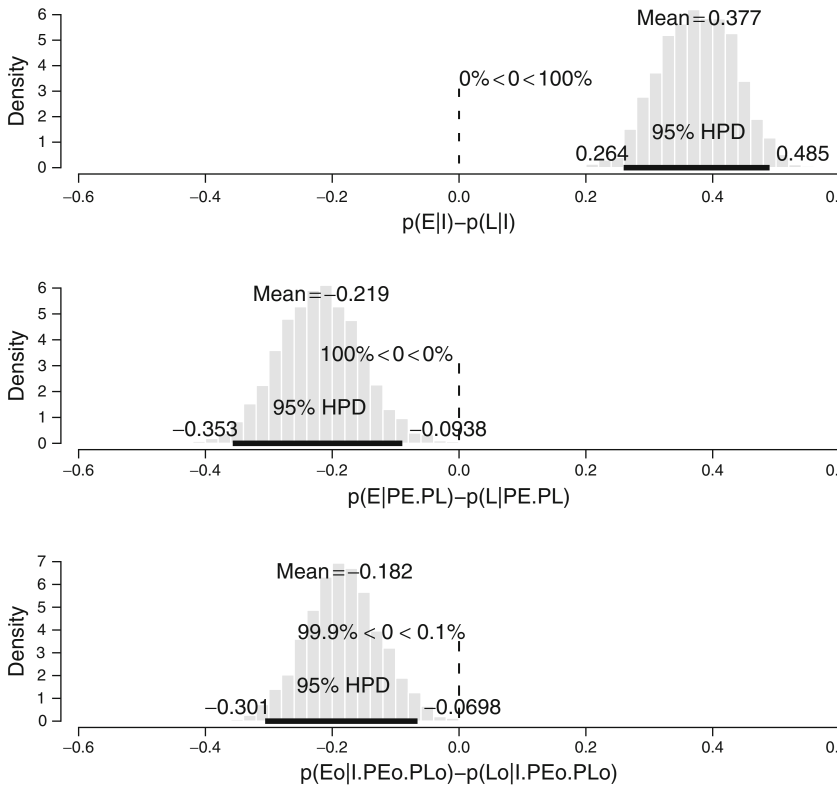

Figure 6 Posterior distributions of response biases for selected cues.

This preference is computed at each of the 5000 points in the posterior, and a histogram of those credible preferences is shown in the top panel of Figure 6. It shows that the mean estimate of $p(E|I) - p(L|I)$ is 0.377, the 95% highest posterior density[3] (HPD) region falls well above zero (ranging from 0.264 to 0.485), and 100% of the believable values are greater than zero. In other words, our posterior beliefs about the response bias for cue I are very firmly that E is preferred over L.

Analogously, the middle and lower panels of Figure 6 indicate that our posterior beliefs are very firmly that response L is preferred to response E for cues PE.PL, and Lo is preferred to Eo for cues I.PEo.PLo. The posterior

[3] By definition, all the points of the 95% HPD region have higher believability than points outside the region, and the region covers 95% of the believable values.

distributions reveal in detail just how believable are various magnitudes of preference. In particular, for cues I.PEo.PLo, the mean of believable values for $p(Eo\,|\,I.PEo.PLo) - p(Lo\,|\,I.PEo.PLo)$ is -0.182, the 95% HPD is well below zero (ranging from -0.301 to -0.0698), and 99.9% of the values are below 0. This bias for cues I.PEo.PLo is especially challenging for the eliminative inference model (Juslin et al., 2001; Kruschke, 2001b).

Another test cases of interest, not shown in Figure 6, is PE.PLo. The posterior for $p(E\,|\,PE.PLo) - p(Lo\,|\,PE.PLo)$ has mean -0.304, 95% HPD ranging from -0.433 to -0.171, and has 100% of its values less than 0. Finally, it is interesting to compare $p(Eo\,|\,I.Eo)$ with $p(Lo\,|\,I.PLo)$. The posterior for $p(Eo\,|\,I.Eo) - p(Lo\,|\,I.Lo)$ has mean -0.161, 95% HPD ranging from -0.253 to -0.067, and has 99.8% of its values less than 0.

The posterior distributions of α parameters are available on the author's Web site. The distributions are useful for two purposes. First, interested readers can examine the believable response propensities for all the test cases. Second, researchers who want to repeat the experiment can use the distribution as a prior for their own analyses.

In summary, the Bayesian analysis indicates that the signature "torsion" of highlighting is highly credible for these data from a canonical highlighting design. The Bayesian analysis avoided the questionable assumption of traditional chi-square analyses, that all individuals have the same response propensities. And unlike chi-square analyses that only indicate whether or not a null hypothesis can be rejected, the Bayesian analysis explicitly reveals the believabilities of various degrees of response preference.

3.3. Implications and Discussion

The main point of the results is that the classic highlighting effect occurs robustly even in a "canonical," equalized base-rates design. In other words, the highlighting effect is not properly called an inverse base-rate effect, because there are no differential base rates to invert. Indeed, as argued by Kruschke (1996), the inverse base-rate effect of Medin and Edelson (1988) is best understood as a case of highlighting in which the differential order of learning happens to be driven by differential base rates; that is, the role of differential base rates is to cause the more frequent cases to be learned before the less frequent cases.

One implication of the results is that theories of learning must be sensitive to order or learning. The highlighting effect occurs because later learned outcomes are learned in the mental context of previously learned outcomes. Theories of learning that are insensitive to learning order will necessarily fail to account for highlighting.

One family of theories that is insensitive to trial order comprises current versions of Bayesian learning models that treat all instances as equally representative data, irrespective of when the trials occurred. In principle, Bayesian learning models are able to incorporate temporal variables, but most current models do not, merely for simplicity. Future Bayesian approaches should include mechanisms that are sensitive to trial order, and, even better, also incorporate attentional learning.

Rather than incorporate explicit learned temporal dependencies into a Bayesian model, a different approach to modeling highlighting is to ‘‘break’’ the Bayesian model so it becomes non-Bayesian. Daw et al. (2008) showed that by applying various restrictions to the Kalman filter (a Bayesian model), which were motivated by different statistical approximation techniques, the approximately Bayesian model could qualitatively reproduce the basic torsion of the highlighting effect. Some approximations yielded the basic torsion, while others did not. It remains to be seen whether any particular approximation to a Kalman filter can exhibit the full set of preferences reported in Table 2 and results from previous studies summarized in the first half of this chapter.

A theorist might be motivated to model highlighting with an approximately Bayesian model if highlighting is appraised as a mere breakdown in an otherwise smoothly operating Bayesian mind. But highlighting is not a mere anomaly, and highlighting is not dependent on straining the limits of human information processing. As was suggested in the first half of this chapter, highlighting is a robust phenomenon that occurs across a variety of situations and with only moderate demands on mental processing. Highlighting is a sign of learning well, not badly.

Instead of asserting that the mind is a poor approximation to a Bayesian model, the Bayesian theorist can maintain that the mind is Bayesian, but at different levels of analysis. Rather than insist that the entire mind is globally Bayesian, it may be that sub-processes or components of mind are locally Bayesian. Clearly there may be learning occurring at many levels: neurons, anatomical partitions of brain, functional partitions of mind, individual persons, committees of people, corporations, and entire societies. Locally Bayesian learning of cue-to-attention mappings and of attended-cue-to-outcome mappings is one candidate for this sort of approach (Kruschke, 2006c).

Another implication of the results presented here is that explanations of the inverse base-rate effect should start with an explanation of (canonical) highlighting, and then include additional considerations for dealing with response biases in the presence of differential base rates. In particular, because the preference for the later learned category, in response to probe PE.PL, persists even when base rates of the response categories oppose that preference, there is likely to be an underweighting of base rates (Johansen et al., 2007; Kruschke, 1996). Indeed, Goodie and Fantino (1999) argued that base rates are rationally underweighted because base rates change more often than cue-outcome contingencies (see Dunwoody, Goodie, & Mahan, 2005, for empirical evidence).

One further implication of the results is that highlighting is not caused by eliminative inference (Juslin et al., 2001). The theory of eliminative inference assumes that response L is given to cues PE.PL because the L category has not been well learned: The L response is given because the well-learned E response is eliminated, and category L is inferred because it is all that remains from the response options. In the canonical design, however, all the categories are very well learned; there are no rare categories that are only weakly learned (cf. Experiment 2 of Kruschke, 2001b).

It is hoped that the canonical design, data, and Bayesian posterior can be profitably applied by other researchers. The canonical design is adaptable to various stimulus types and subject populations. In particular, if the phases are trained to criterion, rather than for a fixed number of trials, genuine learning of the early cases is assured. The computer program that was used for the experiment is available from the author's Web site. Because the canonical, equal base-rate design is particularly challenging to theories of learning, the data can be used as a test bed for models of learning. The complete raw data set is available from the author's Web site. Analysis of future data sets, when using the hierarchical Bayesian model of Figure 5, might also profitably use the posterior beliefs from the present analysis to inform priors for subsequent analyses. The posterior distribution is also available from the author's Web site.

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Appendix: Two general reasons that null hypothesis significance testing has less than ambient pressure

A traditional chi-square analysis might be applied to the data in Table 2, but there are compelling reasons to avoid null hypothesis significance testing (NHST) in favor of Bayesian analysis, in general. One reason to avoid NHST is that it relies on the covert intention of the experimenter to define what it means to replicate the experiment and thereby derive a sampling distribution. The sampling distribution for replicated experiments is the crucial foundation for NHST, because the sampling distribution determines the p value. In traditional NHST, a replication usually assumes that the intention was to fix the sample size N, whereby a replication of the experiment means a random sample of size N from the null hypothesis population. In the present experiment, N was not fixed in advance. Instead, available session times were posted for many hours during a week. Many volunteers signed up. If the supply of volunteers happened to be at a slow rate, the experiment would have been run for another week or two. Only a subset of those who signed up actually showed up for the experiment. On very rare occasions, a computer may inexplicably freeze during an experiment, or a subject might decide to discontinue the experiment. After the data are collected, the learning criterion excludes some unforeseen number of subjects from further analysis. It is absurd, therefore, to consider a sampling distribution in which N is fixed. But all the p values computed by statistical packages, and critical values tabulated in the appendices of textbooks, assume fixed N. More fundamentally, the experiment was designed to insulate the data from the experimenter's intentions, so the experimenter's intention to run $N = 20$ or $N = 200$ should have no influence on the interpretation of the data. The fundamental logic of NHST assumes that the experimenter's intentions *should* determine the interpretation of data, which runs counter to the even more fundamental effort to insure that the experimenter's intentions do *not* influence the data.

There is another reason to avoid NHST: It does not tell us what we want to know. Consider, for example, responses in the test phase to cue I. The data suggest that $p(E|I) > p(L|I)$ in the underlying population, but we would like to know how much we can believe that there is a difference. More generally, we would like to know how much we can believe in any particular difference $p(E|I) - p(L|I)$ in the underlying population. Suppose we conduct a chi-square goodness-of-fit test for a null hypothesis of equal response probabilities across the four response options. The resulting p value tells us the probability of getting a chi-square value as or more extreme than the one we found in our data, were we to repeat the experiment with the same N from the null hypothesis. The NHST p values tells us about the probability of data we might have gotten but did not observe, if we replicated according to covert intentions of fixed N. In principle, we could consider alternative hypotheses and conduct tests of rejection on those alternatives, to construct a range of underlying response probabilities that significance testing would not reject, but this is not done by standard statistical packages and would still rely, nevertheless, on the strange notion of a fixed-N sampling distribution. And, most importantly, it would not tell us how much we should believe in each unrejected set of response probabilities. Bayesian analysis, on the other hand, relies only on the observed data, not on the experimenter's intentions during data collection. And Bayesian analysis tells us what we want to know, namely, the believabilities of underlying response probabilities and their differences.

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CHAPTER SIX

The Emergence of Intention Attribution in Infancy

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Contents

Abstract

Perception of the social world in terms of agents and their intentional relations is fundamental to human experience. In this chapter, we review recent investigations into the origins of this fundamental ability that trace its roots to the first year of life. These studies show that infants represent others' actions not as purely physical motions, but rather as actions directed at goals and objects of attention. Infants are able to recover intentional relations at varying levels of analysis, including concrete action goals, higher order plans, acts of attention, and collaborative goals. There is mounting evidence that these early competencies are strongly influenced by infants' own experience as intentional agents. Action experience shapes infants' action perception.

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1. Introduction

Central to human experience is the perception that we live in a world of intentional agents. We see others' actions not as raw physical movements, but rather as structured by intentions. The intentional lives of our social partners are as real to us as the physical world in which they play out. To illustrate, on seeing a player chase a soccer ball across a field, we conceive of the event not in terms of sheer physical movements, but rather in terms of the player's goal to propel the ball and her more abstract goals to evade the players on the other team, score and win the game. Even though the ball traverses the field along a similar trajectory to the player, we do not view its movements in the same way.

This cornerstone of social perception is pervasive in adults' memory for, reasoning about, and communication of event information (Dennett, 1987; Heider, 1958; Malle, Moses, & Baldwin, 2001; Shipley & Zacks, 2008). For example, on viewing continuous events in which people perform common actions, adults readily parse the events into units that correspond to the goals that structure the agent's actions (Zacks, Tversky, & Iyer, 2001). Further, when relating event information in discourse, adults and children structure their narrative with respect to the goals and higher order plans embedded in the events (Trabasso, Stein, Rodkin, Munger, & Baugh, 1992). Although there are striking cross-cultural variations in social reasoning, the spontaneous perception of others as intentional agents appears to be universal across human cultures (Lieberman, Jarcho, & Obayashi, 2005; Lillard, 1998; Norenzayan & Nisbett, 2000).

Barresi and Moore (1996) described the perception of others' actions as being structured by *intentional relations*: People conceive of others' actions in terms of the agent's intentional relation to a real or abstract entity. To illustrate, when the soccer player turns to face an opponent, observers understand her actions as indicating a relation between her and the other player—she *sees* the opponent. When she drives the ball down the field, observers view her actions in relation to the physical goal, as well as the more abstract goals of scoring a point and winning the game. Intentional relations range from the concrete (getting, wanting, or seeing the ball) to the abstract (wanting to win the game, imagining tomorrow's match, or regretting yesterday's loss). Adults describe these relations via a large mental state lexicon that captures distinct kinds of intentional relations, including relations to goal objects, relations to objects of attention, and relations to mental entities (ideas, plans, beliefs). As Barresi and Moore noted, this rich and varied set of attributions has, at its core, the understanding that human behavior is best understood not as isolated movements through space, but rather as movement in relation to something (a goal, an object of attention, etc.).

In this chapter, our focus is the development of this cornerstone of social perception. As shorthand, we will use the term *intention-reading* to describe the perception of others' actions as organized by intentional relations. Developmental psychologists seek to understand the origins of basic human abilities. Because it is so basic to our everyday perception of reality, the emergence of intention-reading has long been a focus in developmental work. Interest in this topic can be traced back to the earliest days of the field (Piaget, 1929), and this area is still a hotbed of current research and debate.

There is another reason for this prolonged and intense scientific interest in the development of intention-reading: this ability plays a foundational role in broader developmental processes. Much of cognitive, social, and linguistic development depends on the child's ability to discern the intentions of social partners. To illustrate, when 18-month-old children imitate the actions of others, they do not simply reproduce the movements they observe. Rather, they infer the actor's probable intentions and seek to reproduce them. Indeed, Meltzoff (1995) showed that 18-month-old children reproduce the model's intent, even when the model has failed to achieve her goal, and thus they have never actually seen the intended outcome. Similarly, when children at this age learn new words, they do not simply map the words they hear to the objects they see. Rather, they seek and use information about the speaker's focus of attention and intentions to interpret the words she utters (Baldwin & Moses, 2001; Tomasello, 1999). As one example, Baldwin has shown that 18-month-old children infer that an adult's utterances pertain to the object of her attention, even when their own attention is directed elsewhere (Baldwin, 1989). Children engage in a similar process of intentional analysis when making sense of others' emotional signals to decide which objects are safe and which are dangerous (Moses, Baldwin, Rosicky, & Tidball, 2001).

Findings like these support two conclusions. First, the ability to discern intentional relations is critical for many early acts of social learning. This ability provides a lens for extracting the meaningful structure in action (Woodward, 2003b, 2005a). Second, this ability is robust by the middle the second year of life, and thus tracing its developmental origins requires that we look still earlier. In the past decade, researchers have devised methods for tapping preverbal infants' analysis of others' actions. The results of this work have provided strong converging evidence that sensitivity to intentional relations emerges early in the first year of life. In Section 2, we review these findings in order to characterize infants' understanding of intentional relations during the first year of life. This review motivates the question addressed in the second half of the chapter, namely, how intention-reading originates in human ontogeny.

2. Intentional Analysis in Infancy: An Overview

Infants seem socially smart to the adults who interact with them. Young infants are intensely interested in other people, and they engage in well-structured dyadic interactions from the first few months of life (Cohn & Tronick, 1987). By the end of the first year, infants engage in triadic interactions, in which they share attention on objects with an adult, following the adult's gaze to the object, and directing the adult's attention via pointing and other communicative gestures (Bakeman & Adamson, 1984; Bates, Benigni, Bretherton, Camaioni, & Volterra, 1979; Bruner, 1983). A number of researchers have argued that these rich interactions are evidence that infants appreciate others' intentions (Bretherton, 1991; Tomasello, 1995). However, other researchers have pointed out problems with assuming that infants' social responses are direct evidence for their intentional understanding.

To start, infants' social responses may lead to overestimation of their social knowledge because they can often be explained by low-level factors, reinforcement learning, or by adults' management of infants' actions. For example, infants' spontaneous tendency to follow others' gaze shifts has sometimes been argued to reflect tacit knowledge about others' attentional states (i.e., infants are assumed to follow gaze because they know the other person is looking at something). However, as Moore and Corkum (1994) pointed out, infants might follow gaze based on a history of reinforcement for doing so, or based on lower level attentional mechanisms (such as orienting to the movement of the face and/or eyes), without yet understanding that others can be linked to objects via attention (see also Woodward, 2003b, 2005a).

On the other hand, reliance on spontaneous social responses as evidence can also lead to underestimation of infants' intentional action knowledge depending on the criteria used and the complexity of the social responses involved. As one example, Tomasello and his colleagues have developed innovative laboratory procedures for measuring infants' action understanding via their responses to social partners. These studies get around many of the problems involved in reasoning from naturalistic observations, and therefore they support stronger conclusions concerning infants' intentional action knowledge. But the cost of this rigor is that the requisite responses are quite demanding. To illustrate, in one study (Behne, Carpenter, Call, & Tomasello, 2005) infants interacted with an experimenter who repeatedly handed over small toys. One some trials, the experimenter failed to deliver the toy. In some cases, the failed delivery was accompanied by evidence that the experimenter had tried to deliver the toy, but failed. In other cases, the experimenter acted as if she intended to withhold the toy in a teasing manner. Infants 12 months of age and older responded in clearly distinct ways to "unable" versus "unwilling" trials, producing communicative behaviors that suggested annoyance or impatience on the latter but not the former trials. Six-month-old infants did not respond differently on these two kinds trials, leading the authors to suggest that they were unable to discern the experimenter's intentions. However, this failure may reflect the complexity of the testing context and the requisite social responses. Six-month olds do not typically participate in toy exchange games, nor do they produce communicative gestures, each critical elements of the experimental procedure.

As these two kinds of problems illustrate, because spontaneous social behavior is driven by many factors, it often cannot support clear conclusions concerning infants' underlying cognitive processes (see Brune & Woodward, 2007, for a discussion). Over the past decade, researchers have developed tools for more precisely isolating infants' analysis of others' actions. One of the first tools recruited for this purpose was the visual habituation paradigm. This method recruits a minimally demanding response (looking) that is well within the capacity of very young infants and also appropriate for older infants. The logic behind this method is simple: When shown the same event repeatedly, infants attend to it less and less, showing a habituation response. Once infants have habituated, they show recovery (increased visual attention) to events that differ from the habituation event, but only if they detect the difference and find it novel. Thus, infants' patterns of recovery can reveal the structure of their event representations. Critically, for our current focus, we can use this paradigm to ask whether infants show a selective novelty response to changes in the relational aspects of intentional action.

2.1. Instrumental Actions as Goal Directed

Adults interpret even concrete actions not as purely physical motions through space but rather as directed at particular objects or outcomes, that is, in terms of intentional relations. The action depicted in Figure 1 (a person reaches toward and grasps a toy), is a case in point. On one analysis, this is a simple, concrete movement through space. But adults see it in terms of the relation between the agent and her goal ("She grasped the bear.") rather than in terms of the strictly physical properties of the arm's motion.

To test whether infants represent the relational structure of events like this one, we recruited the visual habituation paradigm. Infants first viewed an event, like the one in Figure 1, repeatedly until they had habituated to it. Then, the objects' positions were reversed and infants viewed test events which either disrupted the spatial properties of the reach while maintaining the relation between the actor and the object she grasped (*new-side trials*) or

Figure 1 Stimuli from visual habituation studies of infants' analysis of reaching actions as goal directed.

maintained the spatial properties of the reach while disrupting the relation between the actor and the object (*new-goal trials*). Infants as young as 5 months of age showed a stronger novelty response (i.e., longer looking) on new-goal trials than on new-side trials (Guajardo & Woodward, 2004; Woodward, 1998, 1999).

A second way to examine infants' novelty response is to compare their attention on the test trials to their attention at the end of the habituation phase. Infants might detect the novelty in both kinds of test trials, and thus recover attention relative to the end of habituation, even if they look longer overall at one kind of test trial than another. Interestingly, in these studies, infants typically show recovery of attention on new-goal trials but not on new-side trials. Even though new-side trials present infants with several changes (the toys have been moved, the arm takes a new path and arrives at a new location), infants do not respond to these events as if they were different from the habituation event. This pattern of response suggests that infants represent these actions in terms of the relation between the agent and her goal. When the relation is disrupted, they find the resulting event novel. When the agent-goal relation is preserved, even when other aspects of the event have changed, infants do not show a strong novelty response.

This selective response to goal changes has been replicated in a number of infant laboratories (Biro & Leslie, 2007; Brandone & Wellman, 2009;

Sodian & Thoermer, 2004; Wellman & Phillips, 2001). Critically, infants do not show this response for all events in which one object moves toward and contacts another. They do not respond selectively to "goal" changes when the moving entity is not readily identified as an agent (Hofer, Hauf, & Aschersleben, 2005; Woodward, 1998), or when the action is ambiguous (Woodward, 1999; Woodward & Guajardo, 2002). In these cases, infants respond equally to the change in "goal" and the change in the patterns of movement. Thus, infants' response to goal-directed actions seems not to derive from general properties of the event, such as the way the moving entity entrains attention to the object or the repeated spatial association between the moving entity and the object. Instead, infants' selective response on new-goal trials seems to reflect knowledge about goal-directed action *per se*.

Further evidence for this conclusion comes from studies in which infants are presented with novel or ambiguous agents, for example, a mechanical claw. Infants do not spontaneously respond to the movements of an inanimate object as if they were goal directed; however, infants' tendency to view these events as goal directed can be shifted by contextual cues indicating the animacy of the agent or goal directedness of the action (Biro & Leslie, 2007; Hofer et al., 2005; Luo & Baillargeon, 2005; Shimizu & Johnson, 2004). To illustrate, Hofer et al. found that 9-month-old infants did not view a mechanical claw's actions on an object as goal directed. However, when infants first saw that the claw was manipulated by a person, they subsequently responded to the claw events as if they were goal directed, that is, showing selective attention to changes in the claw-goal relation as compared to changes in the claw's movements.

The findings from these visual habituation experiments led us to ask whether infants' sensitivity to action goals is expressed in behaviors beyond their patterns of visual attention. In other domains of infant cognition, habituation experiments have sometimes revealed knowledge that is strikingly absent when assessed in infants' overt actions. The most well-known example of this kind of dissociation is the case of object permanence. Young infants show evidence of representing hidden objects in looking time experiments many months before they can successfully search for a hidden object (Baillargeon, 1995; Spelke, Breinlinger, Macomber, & Jacobson, 1992).

Is infants' action knowledge similarly limited early in the first year? Younger infants' failures on measures of complex social responses suggest it might be. However, we reasoned that a simpler task might be more successful at revealing young infants' action knowledge. Based on findings with older infants, we predicted that younger infants would selectively imitate the goal of an observed action, so long as the response demands were low and the event was familiar to them. We presented 7-month-old infants with an experimenter who modeled a goal-directed reach toward one of two small toys. Then, infants were given a chance to choose between the toys. In this condition, infants systematically chose the toy that had been the experimenter's goal (Hamlin, Hallinan, & Woodward, 2008). However, when infants saw the adult direct an ambiguous action toward the toy (Hamlin et al.) or saw an inanimate object approach the toy (Mahajan & Woodward, under review), they chose randomly when given the choice between them. Even though all of these kinds of movements led infants to attend to the toy, only one, the human reach, was seen as goal directed, and this interpretation drove infants' responses.

2.2. Higher Order Instrumental Goals

Instrumental goals can be perceived at varying levels of analysis, Goals structure individual actions, and these individual actions can in turn be assembled in service of more abstract goals. For example, in the event depicted in Figure 2, a woman grasps a cloth, and then pulls it toward herself to reach the toy it supports. At one level, we can encode the goals that structure each action (grasping the cloth, grasping the toy), and we also understand these actions as part of a higher order plan (obtaining the toy). Thus, we understand the woman's actions on the cloth as not simply directed at the cloth itself, but ultimately at the toy.

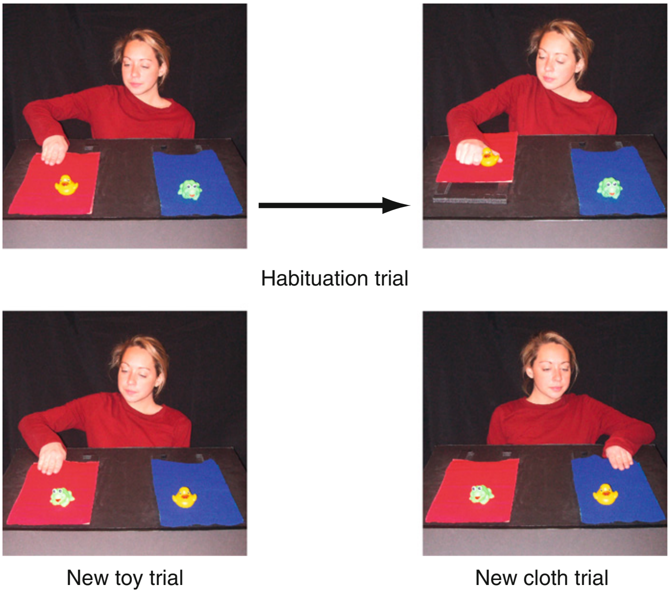

Figure 2 Stimuli from visual habituation studies of infants' analysis of means-end goal structure.

By the end of the first year of life, infants detect higher order goals such as this one. In one study (Sommerville & Woodward, 2005) infants were habituated to the event depicted in Figure 2—a woman pulled one of two cloths to obtain the toy it supported. The question of interest was whether infants interpreted the adult's grasp of the cloth as directed at the cloth itself or instead at the toy. To address this question, after habituation the location of the toys was reversed, and infants saw the adult grasp the same cloth as during habituation, which now held a new toy (new-goal trials) or grasp the other cloth, which now held the toy that had been the goal during habituation (new-cloth trials). Twelve-month-old infants showed a greater novelty response on new-goal trials than new-cloth trials, indicating that they interpreted the reach to the cloth as directed at the toy. Like adults, infants are based their analysis of the actor's goals on the causal relations between them—the grasp of the cloth can be interpreted as directed at getting the toy because it plays a causal role in obtaining the toy (by bringing the toy within reach). Disrupting the causal relation disrupted infants' encoding of the higher order goal: When another group of infants viewed events like those in Figure 2 except that the toy sat to the side of the cloth rather than on it, they did not respond selectively on new-toy trials.

These findings have been replicated using other kinds of means-end sequences, indicating that the ability to analyze higher order goals is relatively general by the end of the first year of life (Sommerville, Hildebrand, & Crane, 2008; Woodward & Sommerville, 2000; see also Gergely & Csibra, 2003). Further, as was the case for reaching actions, infants' analysis of higher order goals is expressed in their imitative behavior as well as their looking times (Hallinan, Hamlin, DeNale, & Woodward, 2007). Taken together, these findings indicate that, by the end of the first year, infants represent plans as independent of the particular actions that are assembled to complete them.

2.3. Attention as Object Directed

Adults represent not only the physical relations between agents and the objects on which they act, but also the invisible relation between an agent and the object of his or her attention. By the end of the first year of life, infants represent this invisible connection. In one study, we showed 7-, 9- and 12-month-old infants events in which an experimenter turned to look at a toy, as shown in Figure 3 (Woodward, 2003a). Infants at all ages reliably followed the person's gaze, turning to look at the same toy she did. Our question was whether infants not only followed gaze, but also understood the relation between the experimenter and the object at which her gaze was directed. To address this question, we used the habituation paradigm developed in earlier studies. Following habituation to one looking event, the objects' positions were reversed and infants viewed *new-goal* test trials

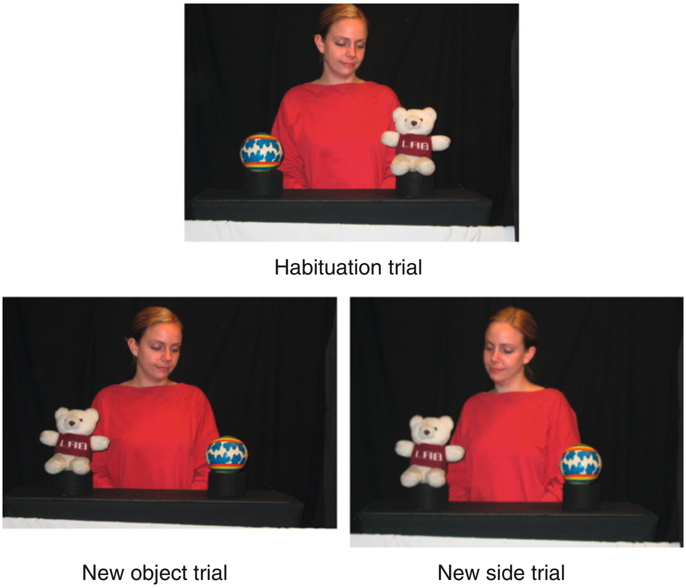

Figure 3 Stimuli from visual habituation studies of infants' analysis of attention as object directed.

which disrupted the object to which the experimenter directed gaze and *new-side* test trials which changed the experimenter's physical motions while maintaining the same object as the target of attention. The 7- and 9-month-old infants did not respond to the change in agent-object relation. In fact, they did not recover attention on either kind of test event. Despite the fact that they had followed the experimenter's gaze to the object, infants at these ages seemed not to represent the relation between the experimenter and object. Thus, infants' social responses, in this case gaze-following, do not always express underlying knowledge about the intentional actions of social partners. In contrast, 12-month olds not only followed the experimenter's gaze, they also responded systematically to the change in agent-object relation by looking longer on new-goal than new-side trials (see also Johnson, Ok, & Luo, 2007; Woodward & Guajardo, 2002).

By 12 months, infants also relate attention to other aspects of a person's intentional actions. Phillips, Wellman, and Spelke (2002) found that 12-month-old infants use gaze direction to predict a person's next actions. Infants at this age expect that a person will reach toward the object at which she has just looked, and detect a violation when she reaches for an object she has not attended to (see also Sodian & Thoermer, 2004). Luo and Baillargeon (2007) found that 12-month-old infants interpret a person's predispositions to act based on what she can see. When an actor chose between two toys with full visual access to both, infants assumed she would continue to reach for that object when given the choice again. However, when the actor at first had no visual access to the unchosen toy, infants did not assume she would choose the target again when given a choice between the two toys.

Onishi and Baillargeon (2005) demonstrated that slightly older infants, 15-month olds, can track a person's attention to an object across displacements, and use this information to predict her next actions (see also Southgate, Senju, & Csibra, 2007; Surian, Caldi, & Sperber, 2007). Because infants assume the agent will return to the place she last saw the object, even when the object has been secretly removed from the location, these findings have been suggested to be evidence for "false belief" reasoning in infants. This interpretation has been challenged (Perner & Ruffman, 2005). Even so, at the very least this work shows that infants are skilled at integrating information about a person's attention to and actions on objects.

These findings highlight the relational nature of infants' action analysis. Infants encode not only the relations implied by individual actions but also relations among these different kinds of intentional relations. The preponderance of evidence for this integration of intentional relations comes from studies of infants 12 months of age or older. However, in a recent study, Luo and Johnson (2009) found that 6-month-old infants condition their action predictions on the agent's prior perceptual access to the objects, as in the Luo and Baillargeon (2007) study. In addition to indicating that the ability to integrate information about intentional relations emerges early, these findings also suggest that infants can encode attentional relations at younger ages than previous findings suggested, perhaps because attentional relations are made more salient when they are accompanied by other object-directed actions (see also Johnson et al., 2007).

2.4. Personal Nature of Goals

For adults, a central organizing principle is the continuity of goals within individual people. Indeed, at the heart of our conceptions of both intentional action and persons is the idea that individual people carry with them goals and behavioral propensities. Adults readily attribute to others enduring personality traits, emotional states, and behavioral propensities based on only "thin slices" of observed behavior (Ambady & Rosenthal, 1992). This ability yields the perception of coherent persons and underlies our ability to interpret and predict others' actions over various time scales, including short-term goals that guide actions in the moment as well as longer term preferences and predispositions. Researchers have long assumed that socioemotional processes such as attachment and stranger anxiety depend on infants' cognitive representations of individuals and their psychological or behavioral propensities (see Thompson, 1998 for a review).

However, until recently, there was little direct evidence concerning whether and when infants track goals as a function of the individual agent.

The findings reviewed so far provide strong evidence that infants represent actions as goal directed, but they do not resolve the issue of whether infants understand goals as attributes of individuals. In principle, infants could encode an event as goal directed without linking this analysis to a particular person. In the first months of life, infants can distinguish between individual faces (Slater & Quinn, 2001) and voices (DeCasper & Fifer, 1980), and they are able to learn about novel face–voice relations (Brookes et al., 2001). These abilities provide the basis for, but are distinct from the ability to conceptualize a person with enduring goals. Do infants link perceptual representations of the individual agent with their analysis of the agent's goal?

We recruited the habituation paradigm developed in our prior work to address this question (Buresh & Woodward, 2007; Henderson & Woodward, under review). We presented 9- and 12-month-old infants with reaching events, like the ones described earlier, except that the experimenter's face and upper body were visible. Infants were first introduced to two experimenters, one male and one female. Then infants in the *two-experimenter* condition saw one-experimenter produce the habituation events, and the other during the test phase. We reasoned that if infants understand goals as attributes of individuals, then they should not generalize goal information from the first experimenter to the second. Knowing what person A intends should provide little insight into person B's goals. A second group of infants saw the same experimenter throughout the procedure (the *one-experimenter condition*). This group showed the same pattern of responding found in earlier experiments—a strong novelty response on goal change trials but not on path change trials. In contrast, infants in the two-experimenter condition did not respond systematically on test trials.

This finding suggested that infants had restricted the goal information to the first experimenter. However, to be sure of this, we first needed to address the possibility that infants' failure to respond systematically in two-experimenter condition was due to the novelty of the second experimenter detracting from infants' ability to attend to her actions. First, we coded and compared infants' attentiveness to the events in the one- and two-experimenter conditions. Infants in the two conditions were equally attentive to the test events overall, and equally attentive to the experimenter's hands and face, suggesting that infants in the two conditions had equal opportunity to encode the relevant parts of the event.

Next we conducted a control study in which infants viewed different experimenters during habituation and test, but this time in the context of an action that should generalize across individuals, the use of a conventional label for one of the objects. The events were identical to those in the two-experimenter condition except that when the experimenters grasped the object, they uttered a label for it ("A mido."). Under these conditions, infants generalized the information provided by the first experimenter to the actions of the second. They looked longer on goal change trials than side change trials. Thus, infants were able to generalize information across agents when it was appropriate to do so. Therefore, their restriction of goal information in the first study was not likely due to the demands on attention and information processing posed by the introduction of the second actor. Our initial findings (Buresh & Woodward, 2007) revealed these patterns most strongly at 12 months. In recent studies (Henderson & Woodward, under review), we have confirmed the same results in 9-month-old infants. Taken together, then, these findings indicate that infants, like adults, use the individual person as the unit of analysis for tracking action goals.

These results converge with emerging findings using different methodologies that may tap similar reasoning in infants. A critical aspect of dispositional understanding in adults involves the recognition that actions stem not only from transitory goals, but rather reflect enduring preferences or dispositions for object, people and activities. Sommerville and Crane (under review) investigated the circumstances under which 9.5-month-old infants view goals as stemming from enduring personal preferences for particular objects. Using a variant of Woodward's (1998) initial paradigm, infants saw habituation trials in which an actor repeatedly selected one of two toys. The actor's toy pursuit was accompanied by either a general remark ("Look. Wow!") or an explicit preference statement about the pursued object ("I like frogs"). Infants next received test trials in which the positions of the toys were reversed and the actor alternated pursuing a new-goal object and the old-goal object. Critically, to investigate whether infants viewed the initial object selection as reflecting an enduring preference, these test trials took place in a different room than the habituation trials. Infants in the explicit preference statement condition, but not the general remark condition, looked longer to the new-goal test events than the old-goal test events. Performance at an individual level was linked to infants' reported language comprehension. A follow-up condition revealed that whereas the preference statement facilitated goal transfer across contexts, it did not lead infants to generalize goals to other individuals. Thus, these findings suggest that, at least under certain circumstances, infants at 9.5 months assume that an individual's action reflects enduring preferences for or dispositions toward particular objects. A critical question for future research concerns the role of language in infants' understanding of preferences as enduring across time and space.

Kuhlmeier, Wynn, and Bloom (2003) tested whether infants would infer stable dispositions in agents shown in an animated film. They showed 12-month-old infants events in which three different geometric shapes (A, B, and C) moved as if they were animate agents. Agent A attempted to climb a steep hill. A's progress was helped by B, who pushed A up the hill, and hindered by C, who pushed A down again. Kuhlmeier and colleagues then tested whether infants would use these events to infer A's subsequent dispositions to act with respect to B and C by showing them test events in which A spontaneously approached either B or C. Infants looked longer when A approached the hinderer, C, than when A approached the helper, B. In later studies, Hamlin, Wynn, and Bloom (2007) obtained the same result in 9-month-old infants. Thus, like our findings, these results suggest that by 9 months, infants infer relatively stable (at least in the short term) goals or dispositions in individual agents.

Results from all three laboratories suggest that infants younger than 9 months may not readily attribute goals or dispositions to individuals. Hamlin et al. (2007) also tested 6-month-old infants and found that they did not generate predictions about A's interactions with B and C, although infants at this age did distinguish between B and C in other ways. In unpublished work (Sootsman Buresh & Woodward, 2005), our group found that unlike 9-month-olds, 8-month-old infants freely generalized goal information from the first experimenter to the second. Surprisingly, they did this even though they readily encoded the goal structure of the events and robustly detected the perceptual differences between the two people. Similarly, Blumenthal and Sommerville (in preparation) found that 8-month-old infants do not extend an individual's goals across contexts even under the most supportive contexts (in the presence of an explicit preference statement). It is not yet known whether these failures at younger ages reflect a general lack of insight into the individual and enduring nature of goals, or instead an inability to integrate the relevant aspects of information from the experimental events (e.g., the actor's face, her manual actions, and goal). This issue awaits further investigation.

2.5. Mental State Content of Intentional Relations

To summarize the conclusions to this point, when infants watch people act, they see more than bodies in motion; they see agents whose actions are structured by intentional relations. The actions of social partners attract and direct infants' attention, but infants do more than simply follow actions; they analyze their relational structure.

These findings leave open the question of how much infants understand about the psychological correlates of intentional relations. For adults, intentional relations are connected to, and explained by, a rich web of folk psychological knowledge. Adults have conceptions of mental states, including desires, perceptions, and intention, that explain the relations between agents and objects. It is possible, however, that infants represent intentional relations in terms of how actions are structured with respect to goal objects and objects of attention without reference to the mental processes that drive actions (see Gergely & Csibra, 2003; Woodward, 2005a). The absence of linguistic evidence from infants makes this issue particularly difficult to resolve.

Nevertheless, the evidence just reviewed suggests that by 9 to 12 months, if not before, infants understand something about the inner correlates of observable actions. Mature folk psychology represents mental states as existing independent of immediate physical actions or connections, as interacting with one another to influence subsequent actions, as residing within the individual agent. Infants' action analysis reflects these properties of mental states. Infants represent the abstract relation implied by acts of attention, and they represent higher order goals as distinct from particular, physical connections, seeing them instead as more abstract plans that organize concrete actions. Infants also engage in reasoning about the relations among different kinds of intentional relations, for example, in conditioning action predictions based on a person's prior focus of attention. Finally, as just summarized, infants understand goals not simply as properties of events, but as specific to the agent who acts and enduring across contexts. Thus although it is unlikely that infants understand others' mental lives in all the ways that adults do, infants understand intentional relations as existing independent of particular concrete actions, as interacting with one another, as residing within the individual and persisting across time and space. Each of these is part of what it means to understand intentional relations in psychological terms.

2.6. Collaborative Actions and Shared Goals

To this point we have considered infants' analysis of goals at the level of individual agents. Discerning individual goals, plans, and states of attention is critical to interacting with and learning from social partners. But if infants only represented individual intentional relations, they would miss much of the informative structure in the social world. Humans have a unique capacity to work together to achieve mutual goals, and much of the structure in the social world involves collaborative activity of this sort (Tomasello, Carpenter, Call, Behne, & Moll, 2005). In collaborative interactions, two (or more) people perform complementary actions to achieve a shared goal. Collaborations support the creation of concrete products (e.g., two people work together to make dinner or build a fence) and the attainment of abstract goals (e.g., a teacher and students cooperate as the class masters new material, members of a community adhere to conventional rules or roles that permit the attainment of social goals). The ability to represent collaborative goals is thus critical not only for making sense of others' actions in the moment, but also, ultimately, for understanding the more abstract goals that structure participation in social and cultural communities (Figure 4).

Figure 4 Stimuli from visual habituation studies of infants' analysis of collaborative actions.

Infants engage in interactions that can be described as collaborative during the first year of life. They participate in well-structured feeding routines (Duncan & Farley, 1990), communicative exchanges (Bates et al., 1979; Bruner, 1983), and cooperative games (Hubley & Trevarthen, 1979; Ross & Lollis, 1987). However, it is not always clear from these observations whether infants represent the shared goal structure of these interactions. An infant who performs the right action at the appropriate time in a routine (e.g., opening her mouth to receive food or taking her turn in a game of stack and topple) may do so based on the local contingencies of the routine rather than on a full understanding of the collaboration.

We have begun to seek clearer evidence concerning infants' understanding of collaborative interactions—asking whether 14-month-old infants represent the complementary actions of two individuals as being directed toward the same goal (Henderson & Woodward, under review). Using the visual habituation paradigm, we showed infants sequences in which one experimenter opened a box and held it open as a second experimenter reached inside to retrieve a toy. The experimenters exchanged smiling looks and nods expressing their mutual satisfaction with the outcome. Our question was how infants understood the actions of the first experimenter. Do infants conceive of this experimenter's goal as the box (the only object that she touched) or do they interpret her actions as enabling the attainment of the toy by the second experimenter? To address this question, we showed infants test events in which the first actor reached toward either the box or the toy. If infants interpreted her goal as the box, then the reach to the toy should seem novel to them. If, in contrast, infants interpreted her goal as the toy, then the reach to the box should seem novel, even though this was the object she had acted on throughout the habituation phase. Fourteen-month-old infants looked longer on box trials than toy trials, indicating that they had interpreted the first actor's goal as the toy, not the box.

Understanding collaboration involves not just detecting shared goals, but also the understanding that the actions of the participants are jointly necessary for the attainment of the goal. Teammates who work together to win a soccer match have collaborated, but the fans cheering from the sidelines have not (unless their cheering has so boosted the spirits of the players that it enables them to press on for the final goal). To assess whether infants engaged in this kind of analysis, we showed a second group of infants sequences identical to those in the first condition except that the toy sat next to, rather than inside, the box. The first experimenter opened the (empty) box, the second experimenter grasped the toy, and they exchanged the same satisfied looks and nods as in the first condition. In this case, however, the first experimenter's actions played no causal role in the attainment of the toy. Infants recognized this disruption—they did not infer that the first experimenter's goal was the toy in this condition.

Taken together, these findings indicate that, by 14 months, infants understand collaborative interactions as involving complementary actions in service of attaining a shared goal, at least in cases of relatively simple, concrete collaborative activities. This ability would allow infants initial access to the goal structure inherent in many social interactions, and thus lay the foundation for learning from and participating in more abstract forms of social collaboration. Our findings at 14 months raise a number of questions. First, how early can infants' sensitivity to collaborative goals be traced? Further, questions remain concerning the kinds of collaborations infants can represent. Do they, for example, understand the collaborative nature of communicative interactions or other acts of socially motivated collaboration? Ongoing research in our laboratory has begun to investigate these issues.

2.7. Summary: Infants' Analysis of Intentional Relations

We began with the observation that adult social perception is grounded in the analysis of human actions in terms of intentional relations. The research summarized so far provides strong evidence that the elements of this social worldview emerge very early in human ontogeny. Infants represent human actions in terms of the relation between agent and object. They see these relations in concrete actions on real objects, in higher order plans that structure sequences of actions, and in acts of attention. Like adults, infants see the person as the organizational unit for intentional relations—they track intentional relations as a function of the person who acts. Further, like adults, infants are not limited to reasoning about the goals of individual people—they can also recover the shared goal structure of collaborative activities.

These elements of social perception emerge by the end of the first year of life, a time when infants have very little, if any, language, and without explicit instruction. They are in place in time to focus infants' social learning in the second year of life. Because infants see others' actions in terms of intentional relations, they are able to glean information from others actions about word meanings, culturally specified forms of behavior, functional properties of objects, and safety and danger. Infants' intention-reading clearly sets the stage for future learning. In Section 3, we consider the epigenetic roots of this ability. What processes give rise to infants' intention-reading?

3. Developmental Origins of Intention-Reading

Our review up to this point has highlighted two facts that any developmental account must explain: The perception of intentional relations is spontaneous and universal in adults, and it emerges during infancy, before children possess the explicit folk psychological knowledge that emerges in early childhood. Further, because intention-reading is so critical for human social functioning and the development of key human abilities, such as language and culture, it is reasonable to assume that it has been shaped by natural selection.

These considerations have led some developmental scientists to stress the role of innate core knowledge in explaining the origins of intention-reading. Several variants of this general proposal have been formulated, each positing that the universality and early emergence of intention-reading is explained by the existence of innate core knowledge about intentions (Biro & Leslie, 2007; Gergely & Csibra, 2003; Luo & Baillargeon, 2005; Premack, 1990). Under these proposals, experience may play a role in shaping the application of the core knowledge to real world cases, but the core representation of intention exists independent of experience. Nature's response to the importance of intention-reading for human survival, under these views, was to build in the core architecture.

Nature could have responded differently. The early emergence and universality of an ability may also reflect the effects of early and universally available experience. Indeed, it is common for developmental systems to recruit information that is reliably present in the environment. This is true not only for learning based on individually variable experiences (like learning to read or play chess), but also for the development of species-typical abilities that are critical to survival (Greenough, Black, & Wallace, 1987; Johnson, 2005; Marler, 1991). For example, bird song, navigation, and social imprinting in various species all depend on information from the environment to develop typically (Gallistel, Brown, Carey, Gelman, & Keil, 1991; Gottlieb, 1991; Marler, 1991). Often, the relevant experiences are reliably present because they are produced by the developing organism itself. Gottlieb's elegant work on imprinting in ducklings is one example: for some species, the duckling's response to the mother duck's call after hatching depends on prenatal exposure to their own calls, produced in the air sac of the egg. Similarly, species-typical human intention-reading abilities may derive important structure from experience, and perhaps experience produced by infants themselves.

Of course development always involves the interplay of inherent structure in the developing organism and structure in the environment. Uncovering developmental mechanisms requires specifying the relative contributions of each of these at different points in development. With this goal in mind, we have begun to explore the extent to which early experience influences infants' intention-reading. Does intention-reading emerge independent of experience in infants? Or, is it shaped by infants' experiences?

3.1. Developmental Relations Between Producing and Perceiving Goal-Directed Action

In considering these questions, we have focused on one potentially informative set of experiences in infants' lives—namely, their own experiences as intentional agents. As in the case of Gottlieb's ducklings, self-produced actions provide reliable input for development. But beyond being reliably present, infants' own actions are potentially structurally informative for intention-reading because infants' actions are structured with respect to external goals from birth (Hofsten, 2004). During the first year, infants undergo several revolutions in their ability to produce coordinated goal-directed actions. One milestone occurs at around 5 months of age, when infants begin to robustly produce smooth object-directed reaches (Bertenthal & Clifton, 1998; Clearfield & Thelen, 2001). A second occurs at around 9 months of age, when infants begin to be able to organize means-end action sequences in service of higher order goals (Piaget, 1953; Willatts, 1999). These skilled actions are the product of extended months of practice during which infants' actions become progressively more organized with respect to goals. We have begun to investigate the possibility that infants' intention-reading is shaped by these developments in their own actions. If the systems that guide action control are accessible to the systems that perceive action, then as infants come to control goal-directed actions such as reaching or tool use, these developments could provide information to structure infants' perception of others' actions.

It has long been hypothesized that first-person experience provides unique insight into others' intentions (Barresi & Moore, 1996; Gallese, 2001; Meltzoff, 2007; Tomasello, 1999). Recent work from our laboratories has provided growing evidence in support of this hypothesis. To start, developments in infants' own goal-directed actions correlate with their tendency to view others' actions as goal directed. At 10 months, infants who are skilled at producing means-end sequences represent the means-end structure of others' actions, but those who are less skilled do not

(Sommerville & Woodward, 2005). Similarly, at 9 months, infants who produce object-directed points understand others' points as object directed; infants who do not yet point do not (Brune & Woodward, 2007; Woodward & Guajardo, 2002). These correlational findings indicate a link between infants' actions and their action perception, but they cannot specify the causal relations that give rise to the correlation. To get a clearer view of the potential effects of acting on action perception, we have turned to intervention studies in which we support infants' ability to engage in a new goal-directed action and then assess the effects of this engagement on their subsequent perception of others' goal-directed actions.

3.1.1. Learning to Reach for Objects

In our first study to address this issue (Sommerville, Woodward, & Needham, 2005), we intervened with infants who are very limited in their perception and production of goal-directed actions—3-month olds. In our pilot habituation studies, infants younger than 4–5 months of age had never shown systematic responding to goal changes, despite our best efforts to make the procedure as simple as possible. In addition, 3-month-old infants are generally not able to produce coordinated object-directed reaches (Bertenthal & Clifton, 1998; Clearfield & Thelen, 2001). However, Needham, Barrett, and Peterman (2002) found that infants at this age can learn to apprehend objects by swiping at them while wearing Velcro-covered "sticky mittens," as depicted in the first photo in Figure 5. After discovering that the mittens can apprehend objects, infants begin to act on objects in more organized ways, looking at the object while aiming swipes toward it.

To assess whether mittens experience affects infants' perception of others' actions, we gave one group of infants practice with sticky mittens and then tested them in a habituation paradigm like the one depicted in Figure 1. We wanted to maximize infants' ability to detect the similarity

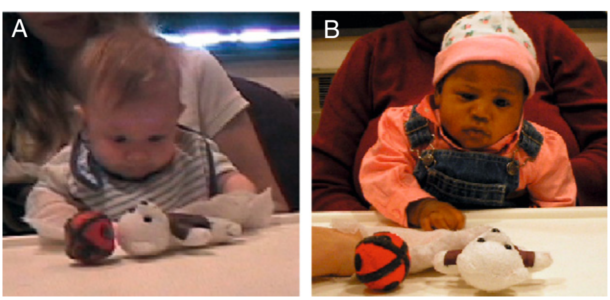

Figure 5 A 3-month-old infant uses "sticky mittens" to apprehend toys in the active condition (A); another 3-month-old infant watches mittened actions in the observation condition (B).

between their own actions and those in the habituation events, and so we used objects in the habituation events that were larger versions of the ones on which infants had acted and had the presenting experimenter wear an adult-sized mitten.

This procedure was a demanding one for such young infants. Given 3-month-old infants' limited attention spans, as well as their frequent need for naps and feedings, the training had to be very short in order for infants to be able to complete the subsequent habituation procedure. This meant that infants had only 3–5 min opportunity to use the mittens before the habituation paradigm began. Even given this limited amount of practice, mittens training had a powerful affect on infants' responses to the habituation events. Following mittens training, infants showed a marked increase in attention on new-goal as compared to new-side test trials, responding like older infants typically do in response to goal-directed actions. In contrast, a control group of infants, who viewed the habituation events without prior mittens experience, did not respond differentially to new-goal versus new-side test trials.

Although mittens experience increased infants' object-directed activities on average, there was also individual variation in infants' level of activity during the mittens training. This variability allowed us to investigate the aspects of the training experience that were critical for infants' response to the goal structure of the actions they observed in the habituation paradigm. In particular, we asked whether it was engagement in object-directed activity *per se*, independent of general visual familiarity with the mitten and toys that was critical. Our findings confirmed that it was the former, not the latter aspect of experience that mattered. The degree to which infants engaged in object-directed actions with the mittens (as indexed by coordinated manual and visual contact with the object) was strongly correlated with their subsequent selective response on new-goal trials. Infants' total visual engagement with the toys was not reliably correlated with their subsequent responses in the habituation paradigm.

These findings showed that infants' own object-directed actions influenced their subsequent perception of others' actions as goal directed, but there still remained a question about the nature of the information that their own actions provided. One possibility is that infants created for themselves a set of informative visual events. They saw their hands reach for, apprehend and move objects, and perhaps these regularities were sufficient to provide information about the relational nature of the actions. Indeed, Biro and Leslie (2007) have suggested that infants use these visual cues to identify goal-directed action. In this case, infants' learning from their own actions would be no different from their observational learning from others' actions. Alternatively, self-produced actions may provide unique information about action structure that could not be gleaned from observation alone. If action production systems provide structure for action perception, then we would predict that self-produced actions would have a unique effect on infants' action perception.

To investigate these issues, we next compared the effects of active mittens training to the effects of closely matched observational experience (Gerson & Woodward, under review). We first sought to replicate the prior effect of active experience on infants' action perception with a slightly larger sample than in the earlier study. As was the case in the first study, we found a tight correlation between infants' own object-directed actions with the mittens and their subsequent selective attention on new-goal compared to new-side trials. In this larger sample of infants we were also able to more closely analyze the nature of this correlation. We found that the function that related infants' reaching actions to their looking time preference was logarithmic rather than linear. This result suggested a threshold effect, such that a minimal level of experience was required to induce a systematic preference for new goal over new-side trials. Given the constraints of the experimental context, the required experience level was relatively low (infants needed to achieve 45 s of object-directed activity within the 3 min training phase). Even so, these findings suggest that a minimal level of expertise is needed to support infants' propensity to see observed actions as goal directed.

Because individual variation in active mittens experience was so closely tied to infants' looking time responses, we sought to obtain similar variation in infants' experience in the observational condition. To do this, we yoked each infant in the observation condition to an infant in the active condition. Each infant viewed an adult producing mittened actions according to a script generated from an infant in the active training condition. We coded infants' attention to the modeled actions on line and then again after the fact from video to ensure that they had attained the scripted level of observational experience.

The yoked design meant that infants in the two conditions received similar levels of experience on average, and also similar degrees of individual variation in experience. This allowed us to assess not only any group level effects of training, but also whether there were correlations or threshold effects in the observational condition, similar to those seen in the active condition. It seemed possible that observational experience could have similar, but less robust effects on infants' subsequent looking time responses. In this case, infants' degree of observational experience might correlate with their subsequent preference for new goal over new-side trials, even in the absence of a group level preference for new goal over new-side trials.

Our findings in this condition revealed none of the potential relations between infants' observational experience and their responses in the habituation paradigm. Neither infants as group nor infants with high levels of observational experience showed any reliable differences on test trials. Further, there was no indication of a correlation between the amount of observational experience infants received and their degree of preference for new goal over new-side trials.

These findings suggest that self-produced experience had a unique effect on young infants' perception of others' goal-directed actions. Indeed, it is possible that very young infants may only succeed in detecting action goals when they have the support of their own actions to do so. Three-month-old infants do not recover the goal structure of reaching events when tested in our visual habituation experiments without active experience (Sommerville et al., 2005), and the earliest reports of goal encoding in these kinds of paradigms in the absence of action interventions are in infants 5–6 months of age (Biro & Leslie, 2007; Brandone & Wellman, 2009; Wellman & Phillips, 2001; Woodward, 1998, 1999).

3.1.2. Learning to Organize Means-End Action Sequences

Self-produced actions strongly affect infants' earliest abilities to discern the goal structure of others' concrete actions. Toward the end of the first year both infants' actions and their analysis of others' actions become increasingly abstract. Infants begin to organize their own actions in means-end sequences, and they also begin to understand that others' actions can be organized as means to an end. To illustrate, as we described earlier, having been habituated to the cloth-pulling sequence at the top of Figure 2, 12-month-old infants looked longer on new-toy than new-cloth trials. They understood that the woman's actions on the cloth were directed not at the cloth itself, but rather at the toy that was drawn near by her actions on the cloth.

Do infants' own actions contribute to their ability to analyze others' higher order goals? Initial evidence on this issue came from a study in which we tested 10-month-old infants in the paradigm depicted in Figure 2 (Sommerville & Woodward, 2005). In contrast to 12-month-olds, 10-month-old infants showed no strong group tendency in their responses on the test trials, varying in their relative attention to new-cloth and new-toy trials. We also found variability in 10-month-olds' own actions when they were confronted with a cloth-pulling problem. Some infants were able to form well-organized solutions most of the time, pulling the cloth while attending to the toy, and grasping the toy when it came within reach. Other infants, in contrast, did this less often, instead straining toward the toy or becoming distracted by the cloth. The variation in infants' own actions correlated with their responses in the visual habituation paradigm: infants who produced more well-organized means-end solutions showed a stronger tendency to view the observed actions as directed at the toy, rather than the cloth.

Following from these findings, we next asked whether training to boost infants' means-end actions would lead to changes in their perception of others' means-end actions (Woodward, Mahajan, & Sommerville, in preparation). We tested 8-month-old infants, who are limited in their ability to organize means-end actions. One group of infants (*the active condition*) was presented with repeated opportunities to solve cloth-pulling problems, interspersed with a block of training trials in which the experimenter first demonstrated a solution and then immediately presented the same problem to the infant, as depicted in Figure 6. Infants benefited from this training. They spontaneously produced well-organized solutions only about a third of the time prior to training but produced well-organized solutions nearly two-thirds of the time on average by the end of the training trials.

After this training, infants' response to observed means-end actions was tested as described earlier and depicted in Figure 2. We found a strong correlation between infants' own actions and their responses to the observed actions: infants who produced high levels of well-organized solutions after the training phase looked reliably longer on new-toy than new-cloth trials, whereas infants who produced few well-organized solutions after training did not differentiate between the test trials. Thus, infants who benefited from training in their own actions also showed more advanced patterns of responding to the observed events.

To assess whether this effect on infants' action perception depended on self-produced experience, we tested a second group of infants who saw an adult perform well-organized cloth-pulling solutions repeatedly but did not get to act on the cloth or toy themselves (*the observation condition*). Infants in this condition were matched to individual infants in the active condition in terms of the total amount of time they spent engaged in or watching cloth-pulling actions. Because infants tended to take longer than the experimenter to produce a well-formed solution, infants in the observation condition viewed more exemplars of good solutions than did infants in the active condition. Further, infants were highly attentive to the training events, closely watching each phase of the action on the majority of trials. Even so, these infants did not benefit from what they saw: They did not respond systematically to the test events in the subsequent habituation procedure and there was no correlation between their degree of observational experience and their subsequent responses in the habituation paradigm.

Figure 6 An 8-month-old infant learns to engage in cloth-pulling actions.

Sommerville et al. (2008) obtained similar findings when they trained 10-month-old infants to use a cane to retrieve a distant toy. Using canes as tools is a novel and difficult task for infants at this age. On pretest trials, infants succeeded at retrieving the toy only about 30% of the time. Infants benefited from training and practice using the canes, however, succeeding close to 70% of the time following training. Critically, infants who received active training also responded systematically to observed cane-pulling actions in a paradigm analogous to the one depicted in Figure 2: Infants looked longer on new-toy trials than new-cane trials, and this effect was especially strong for those infants whose own actions were most well-organized after training. In contrast, infants who observed an experimenter using the cane under conditions matched to the active condition did not respond selectively to the means-end structure of the observed actions.

These two studies converge in indicating that self-produced actions continue to strongly influence infants' action analysis as both abilities become more abstract with development. Infants learned something from engaging in means-ends actions themselves that they were less able to learn from watching others act. Active and observational training each demonstrated the same sequence of actions (pull the cloth, then grasp the toy) and each provided infants with information about the physical structure of the problem (i.e., that the moving cloth would pull the toy within reach). But infants' own actions seem to have provided them with clearer evidence concerning the goals that organized the action sequence and made use of the physical properties of the problem.

While these findings with older infants are consistent with our results at 3 months, they seem inconsistent with other findings in 9- to 12-month-old infants. By these ages (and perhaps earlier) infants are able to analyze the goal structure of novel events in which one entity moves toward another, such as the movement of a claw or pointer toward an object (Biro & Leslie, 2007; Hofer et al., 2005), the movement of a self-propelled or socially interactive object toward another object (Luo & Baillargeon, 2005; Shimizu & Johnson, 2004), or the movement of one geometric shape toward another shape (Gergely et al., 1995; Kuhlmeier et al., 2003). While infants do not spontaneously view these events as goal directed, the presence of movement and/or featural cues that suggest agency can sometimes lead them to do so.

Given these findings, it may seem surprising that infants in the means-end training studies were unable to extract useful information from the experimenter's actions in the observation condition. The training events offered a rich set of cues to the experimenter's goals. She moved the toy toward herself, grasped it, and expressed pleasure at getting it. Why were infants not able to use these cues to infer the experimenter's higher order goal? In addressing this question, it is important to consider two differences between the training studies and the "novel agent" studies described above. First, the means-end training studies assess infants' understanding of higher order goals, in contrast to the novel agent studies, which generally involve single movements toward and contact with an object. Second, unlike the novel agents studies, the training studies required generalization of structural information from one event (in training) to another event (in the habituation paradigm). Given the design of these studies, infants must recruit information about the goal structure of the relevant actions, rather than specific information about the particular goal of the agent.

These considerations suggest two possible explanations for the apparent differences in infants' response in novel agent and training studies. First, agency cues may be sufficient to support the generalization of an existing action representation to a novel instance, but not sufficient to establish a new, more abstract action representation. The movements in many novel agent studies are sufficiently similar to grasping that, given supportive cues, infants may be able to extend their knowledge about grasping to these events when other cues strongly suggest the presence of an agent. But to make sense of the cloth-pulling events, infants must come to see a new level of action structure—the plans that organize individual actions in service of an ultimate goal. This new insight may require input from infants' own actions.

A second possibility is that infants even if infants are able to make sense of the experimenter's means-ends actions in the training context, they may be uncertain about how this structural information should be extended to new events. In the training studies, infants must take information from one event in the training context and use it to make sense of another event in the habituation booth. In comparison to observed events, infants' own actions may lead to more robust, flexible, or enduring structural representations that as a result are more readily generalized to new contexts.

These considerations highlight the question of whether infants' own actions provide insights into goal structure that they could never glean from observation alone, or instead simply provide more salient information than is generally provided by observation. The fact that infants sometimes respond to unusual events as goal directed has led several researchers to conclude that self-produced action cannot be the only source of goal representations, and that, instead, infants must be innately endowed with abstract goal concepts (Biro & Leslie, 2007; Gergely, Nadasdy, Csibra, & Biro, 1995; Luo & Baillargeon, 2005; Shimizu & Johnson, 2004). It is possible that multiple systems, including both self-produced actions and specialized perceptual modules, give rise to relational action representations (see Sommerville et al., 2008; Woodward, 2005a). However, it is also possible that infants' ability to discern goal structure in novel events depends on the analogical extension of action representations that they initially acquired in the context of their own actions (see Gerson & Woodward, in press). Further research is needed to resolve this question.

3.1.3. Learning About Attention

Do infants' own actions uniquely inform their understanding of the relation between an agent and the object of her attention? There is not yet conclusive evidence to answer this question, but two preliminary findings suggests they might. To start, we found correlations between infants' own pointing and their understanding of others points: At 9 months, infants who point at objects also understood others' points as object directed in a variant of our habituation paradigm (Brune & Woodward, 2007; Woodward & Guajardo, 2002). Because infants' earliest pointing behaviors seem egocentric, focused on highlighting objects of attention for themselves (Bates et al., 1979), we speculated that infants' production of points may highlight the attentional connections expressed in others' points (Woodward, 2005b). Of course without intervention studies, this hypothesis remains speculative.

A recent intervention study conducted by Meltzoff and Brooks (2008) provides further evidence that infants gain insight into others' states of attention from their own experience. In prior work (Brooks & Meltzoff, 2002), these researchers had investigated infants' responses to blindfolded adults in a gaze-following task. Older infants, 18-month olds, inhibited their spontaneous tendency to follow gaze when the adult wore a blindfold, suggesting they understood the impact of the blindfold on visual experience. In contrast, 12-month olds continued to follow the adult's gaze when she was blindfolded, suggesting they did not understand the implications of the blindfold. Meltzoff and Brooks gave 12-month-old infants experience wearing the blindfold themselves and found that with this experience, infants subsequently inhibited gaze-following when interacting with the blindfolded adult. Thus, self-produced experience with the blindfold seemed to give infants insight into the perceptual experience of others in the same situation. From these findings, however, it is not clear whether the self-produced nature of the experience was important. More research is needed to investigate this possibility.

3.2. How Does Acting Affect Action Perception?

Our findings show that infants' own actions provide critical information for understanding the actions of others. These results then raise the question of the mechanisms by which information from action production affects action perception. One possibility is that this process depends on forming an analogy between self and other. Analogical processes have been shown to be powerful mechanisms for extracting and generalizing knowledge in older children (Gentner & Medina, 1998), and it is plausible that these processes operate in the development of infants' action knowledge (Gerson & Woodward, in press). In their seminal analysis, Barresi and Moore (1996) hypothesized infants recruit their awareness of their own actions and intentional relations to create a structural analogy with the actions of others. This analogy would allow infants to infer that others' observable actions reflect the same kinds of underlying intentional relations that their own actions do. Under this account, collaborative action and joint attention between infants and caretakers would be critical for the development of intentional understanding because these interactions provide opportunities to align one's own intentional relations with those of others (see also Tomasello, 1999).

Alternatively, information from self-produced action may be extended to others more directly because overlapping neurocognitive representations serve to represent one's own and others' actions (Decety & Sommerville, 2003; Gallese & Goldman, 1998; Gerson & Woodward, in press; Meltzoff, 2007; Sommerville et al., 2005). To illustrate, Meltzoff's (2007) "Like me" framework begins with the supposition that there is a common cognitive representational format for self-produced and observed actions from birth. These *supramodal* representations reflect the common structure of actions of the self and actions of others, independent of the particular modalities by which these actions are perceived (e.g., kinesthetic vs visual). This shared representational format explains neonatal imitation and provides the foundation for constructing increasingly more abstract concepts of intention in oneself and others.

In support of this view, recent findings have documented the existence of shared neural representations for the perception and production of action (sometimes called mirror neurons or mirror systems) in adult nonhuman and human primates (Ferrari, Rozzi, & Fogassi, 2005; Fogassi et al., 2005; Grezes & Decety, 2001; Iacoboni et al., 2005; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996). These mirror systems have properties that suggest they could be involved in the development of intention-reading (see Gerson & Woodward, in press). For one, mirror systems code goal directed or meaningful actions, rather than physical movements *per se*. Further, mirror systems are shaped by motor learning: adults with expertise in specialized actions like classical ballet dancing or using chopsticks show heightened mirror system responses when viewing these actions compared to nonexperts (Calvo-Merino, Grezes, Glaser, Passingham, & Haggard, 2006; Järveläinen, Schürmann, & Hari, 2004). These properties of mirror systems in adults suggest the possibility that during development, infants' emerging abilities to produce goal-directed actions could be recruited for the perception of others' goals.

There is increasing behavioral evidence compatible with the hypothesis that mirror representations exist in human infants, including neonatal imitation (Meltzoff & Moore, 1977), and much of the work summarized in this section of the chapter (see also Cannon & Woodward, in preparation; Falck-Ytter, Gredebäck, & von Hofsten, 2006; Lepage & Theoret, 2007; Longo & Bertenthal, 2006). However, given the limited range of neuroimaging techniques that can currently be used to study infants, there is very little direct neural evidence for mirror systems in infants. One recent study from Southgate, Johnson, Osborne, Karoui, and Csibra (under review) sought evidence from infants for a pattern in EEG responses that had been discovered in adults. When adults plan a motor movement, there is disruption in alpha activity over motor cortex (also known as the mu-rhythm), and this same disruption occurs when adults view others' goal-directed actions (Muthukumaraswamy, Johnson, & McNair, 2004). Southgate and colleagues found a similar pattern of alpha suppression over motor cortex in 9-month-old infants when they viewed human goal-directed actions (reaching) but not when they viewed nonsensical human movements. These findings provide compelling neural evidence for mirror systems in infants and they point the way to future studies investigating the functional and developmental properties of these neural representations in infants (see also Shimada & Hiraki, 2006).

Even assuming a strong role for mirror systems in the development of intention-reading, we believe that conceptual learning mechanisms, including analogical mapping, also play an important role. These processes may explain how infants generalize action knowledge to novel or unusual events, and how they move from action-level knowledge to more explicit, folk theoretic knowledge (see Gerson & Woodward, in press). Furthermore, analogy has also been shown to contribute to developments in infants' own actions, for example, in providing a basis for generalizing means-end solutions to new problems (Chen, Sanchez, Polley, & Campbell, 1997), and this process, in turn, may broaden infants' ability to discern others' intentions.

3.3. Summary: Origins of Intention-Reading

Our findings indicate that human intention-reading is like many other species-typical abilities in that the ontogenetic processes that guarantee the emergence this ability recruit information that is readily available in the context of development. In this case, as in some others, the relevant information is produced by infants' own actions. As infants learn to organize their actions with respect to goal objects, they also gain new ways of perceiving structure in others' actions.

These findings raise a number of questions to focus future research. To start, how broadly do infants generalize information from their own actions? In these first studies, because our goal was to maximize the chances of findings effects of experience on intention-reading, we have been careful to match infants' own experience closely to the actions they view in the habituation in terms of the actions, tools and goal objects. However, if self-produced action is to contribute significantly to infants' intention-reading, infants must be able to generalize appropriately to a broader range of new events. Work underway in our laboratory investigates the question of when and how infants generalize action knowledge to new instances.

A second question is whether infants' own actions inform aspects of their intention-reading beyond the encoding of instrumental action goals (and perhaps attention). As we reviewed in the first part of this chapter, infants show early abilities to integrate information about different kinds of intentional relations, to link goals to individuals, and to recover the shared goal structure of collaborative actions. We do not yet know whether infants' own actions play a role in shaping these aspects of intention-reading, but it seems possible that they do. For example, infants' engagement in collaborative activities with adults toward the end of the first year of life may provide a context in which they can begin to discern shared goals.

Finally, these findings raise the question of how infants' emerging understanding of intentional relations interacts with other kinds of early social learning. It is clear that experience contributes to other aspects of infants' social knowledge, including the formation of social categories (Quinn, Yahr, Kuhn, Slater, & Pascalis, 2002), the recognition of familiar faces and voices (DeCasper & Fifer, 1980), and the formation of expectations concerning the typical actions of caretakers (Johnson et al., 2007). The current findings raise the question of whether learning about these aspects of the social world depends differentially on self-produced versus observational experience. Further, they raise the question of how infants' emerging understanding of others' intentions interacts with learning about social categories, familiar social partners, and common patterns in the behavior of individuals or groups.

4. Conclusions

Classic theories of early cognitive development held that the everyday experience of the infant was a chaotic jumble of unstructured sensory input (Piaget, 1953). Infancy research over the past several decades has put this idea to rest with respect to infants' experience of the physical world (Baillargeon, 1995; Spelke et al., 1992). Only recently, however, have we begun to learn that infants are also skilled at seeing order in the social world.

The findings we have reviewed here support a number of conclusions concerning infants' intention-reading: Early in the first year, infants discern the relational structure of concrete, instrumental actions. By the end of the first year, infants are sensitive to higher order action goals, to relations between agents and the objects of their attention, and to relations among a person's focus of attention and his or her instrumental actions. Infants represent goals as specific to the individual person, but by early in the second year infants can also discern the shared goals that organize collaborative actions. In short, like adults, infants perceive a social world populated by agents whose actions embody intentional relations at varying levels of analysis.

When infancy researchers discover very early competencies this can invite the conclusion that these competencies are largely innately specified, arising independent of experience or learning. This conclusion was the first one drawn from findings of early competence in the physical domain (Spelke et al., 1992). More recent work has begun to uncover the role of early learning in infants' physical knowledge (Baillargeon, 2004; Johnson, Davidow, Hall-Haro, & Frank, 2008), and the field has taken a new interest in the role of experience in infant cognitive development more generally (Woodward & Needham, 2009).

Infants' intention-reading is fertile ground for this new perspective. As we elaborated in the second half of our review, mounting evidence indicates that experience contributes critically to infants' competence in the social domain. Specifically, infants' intention-reading is linked to developments in their own actions: As infants become able to organize actions with respect to goals, they also become able to see intentional structure in others' actions. Indeed, our findings suggest that self-produced experience provides infants with particularly strong, perhaps unique, insights into others' intentions.

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CHAPTER SEVEN

Reader Participation in the Experience of Narrative

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Contents

Abstract

In this chapter, we outline a participatory perspective on readers' experiences of narrative. The perspective asserts that readers function as side participants to narrative events: They encode participatory responses as reactions to characters' utterances and actions. We review a series of empirical projects that illustrate consequences of reader participation. Those projects demonstrate, for example, that the preferences readers develop for particular narrative outcomes affect the time course with which readers assimilate the outcomes that actually obtain. The body of empirical work supports the importance of the participatory perspective to enrich theories of text processing.

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1. Introduction

In Richard Russo's (2007) novel, *Bridge of Sighs*, Lou (also known as Lucy) Lynch narrates his life story. Near the beginning of the novel, Lou relates events that transpired when he was in second grade. He is waylaid by a group of public school kids (Lou goes to parochial school) who lead him, none too gently, toward some unknown destination: "When I lagged or showed any reluctance to get too far from home, they shoved me forward, hard, and took turns cuffing me on the back of the head and asking if I was a girl, since I had a girl's name" (p. 26). It is difficult to imagine that any reader could experience these narrative events without having an overwhelming sense of impending doom.

In fact, it is difficult to imagine that any reader could experience these events without offering Lou some urgent mental assistance: "Run away! Escape!" As the situation evolves, it acquires more subtleties. The public school kid's ringleader, Jerzy, tries to give Lou a sense of security: "I was informed that he and his friends had started a charitable club, the purpose of which was to assist the unfortunate, cripples and widows and the like" (p. 26). Jerzy wishes Lou to believe that his captors are merely trying to recruit him for their club. Jerzy's claim provides readers with an opportunity to offer Lou more specific advice: "Don't believe him!"

We provide these examples of readers' potential mental advice to illustrate what it means for readers to participate in narrative worlds. In this chapter, we provide an overview of a participatory perspective on narrative processing. We begin by describing how this perspective emerges from a theoretical account of conversational language use. We then exemplify some types of participatory responses that readers encode in the course of their narrative experiences. These analyses enable us to describe how the participatory perspective supplements canonical theories of text processing to provide a fuller account of readers' experiences. Finally, we describe several empirical projects that emerge from the participatory perspective and that confirm the theoretical implications of reader participation.

Throughout the chapter, we use excerpts from *Bridge of Sighs* to motivate our analyses. The novel is beautifully written but otherwise has no properties that make it distinctive within the vast category of published fiction. The types of reader participation we describe should accompany virtually all ordinary narrative experiences. However, with *Bridge of Sighs*, Russo has provided us with a particularly pleasurable way to illustrate our phenomena.

2. The Participatory Perspective

The core claim of the participatory perspective is that *readers regularly encode the types of mental contents they would encode were they really participants in the narrative's events*. In this section, we support that claim from analyses of language use in ordinary conversation. We reflect on the mental contents of participation and then briefly review some relevant social psychological research. Finally, we situate the participatory perspective with respect to the classic theoretical agenda of text processing research.

2.1. Side Participation in Ordinary Conversation

Most analyses of conversational language focus on speakers and addressees (e.g., Austin, 1962; Bach & Harnish, 1979; Searle, 1969). However, Clark and Carlson (1982) made the important observation that conversations regularly involve more than two individuals. They offered an innovative theory to explicate how language users function with respect to a more realistic accounting of conversational roles. Consider their example (p. 332):

> Othello, to Desdemona, in front of Iago and Roderigo: Come, Desdemona.

With respect to classic accounts of language use, it is easy to characterize the speech act that Othello has performed with Desdemona as his addressee: He has made a request of her. However, as Clark and Carlson noted, speech act theories were silent on Othello's intentions with respect to Iago and Roderigo. Clearly, some act has taken place. We would expect that Iago and Roderigo have encoded Othello's request in some way, although he clearly does not expect them to do anything in particular (i.e., it is not their responsibility to "come").

Clark and Carlson suggested that Iago and Roderigo are *side participants* in this conversation. The essence of that role is that the speaker, in this case Othello, wishes for it to be the case that side participants be *informed* by the utterance. Clark and Carlson's major innovation was to suggest that, whatever else they are doing, speakers are always performing *informative speech acts*. Clark and Carlson articulated the *informative hypothesis* (p. 333):

> The fundamental kind of participant-directed illocutionary act is one by which the speaker jointly informs all the participants fully of the illocutionary act that he is simultaneously performing toward the addressee or addressees.

Thus, Othello has informed Iago and Roderigo (and also Desdemona) that he is making a request of Desdemona. Clark and Carlson argued persuasively that speakers perform an informative act every time they perform an utterance. That claim generates the immediate corollary that people must have a vast amount of experience being informed by language that is not addressed to them. As such, people must be in possession of cognitive processes that allow them to be so informed.

The central claim of the participatory perspective is that readers are side participants: They use the same repertory of cognitive processes that function in conversational circumstances to be informed by narrative speech acts. Thus, when Owen Lynch makes a request of his mother, Sarah, ''Watch him, Ma,'' (Russo, p. 5) readers are cast in the same role as Iago and Roderigo. The request is not directed to them, but they are informed that Owen wishes his mother to keep an eye on his father.

Clark and Carlson made another important observation about side participants: Speakers hold them responsible for the content of their informative acts. Consider this example (p. 335):

> Charles, to Ann, in front of Barbara: Did you like the museum?
> Ann, to Charles, in front of Barbara: Yes, I did.
> Charles, to Barbara, in front of Ann: What about you?
> Barbara, to Charles, in front of Ann: I liked it too.

In this example, Charles holds Barbara responsible for the content of the conversation that precedes his question to her: He expects that she has been duly informed by the earlier utterances and is prepared to take her turn as addressee. Thus, side participants are not merely passive recipients of informative. Rather, they must be actively engaged in a conversation in a way that makes them ready to function as addressees and speakers. For example, it would seem likely that Barbara would have already formulated some of her own thoughts about the visit to the museum even though she was a side participant, rather than the addressee, when Charles asked his question.

Similarly, we believe that readers, as side participants, will be cognitively engaged as a text unfolds. Consider an interchange that happens early in *Bridge of Sighs*. The conversation begins with a statement by Sarah. Lou is the first-person narrator in the responses (p. 5):

> ''In Venice there is something classed *aqua alta*. High water.''
> ''How high?'' I said.
> ''The *calles* flood.''
> ''What's a *calle*?''
> ''If you'd so some reading, you'd know that streets in Italy are called *calles*.''

Neither question is addressed to the reader. However, readers who have experience in Venice, or have passing knowledge of Italian, are nonetheless likely to encode answers to Sarah's questions. In Section 2.2, we suggest that readers encode a variety of different mental contents as side participants to narrative events.

2.2. Participatory Responses

The participatory perspective suggests that readers encode the same variety of responses they would encode were they side participants in real-world events. Consider a pivotal moment in *Bridge of Sighs*. Throughout the novel, Sarah has been waiting patiently for a response to a letter she sent to her old friend Bobby Marconi. Finally, Lou reveals that he intercepted the letter. Lou is the first-person narrator (pp. 465–466):

> "I steamed the envelope open," I confess, feeling my cheeks burn.
>
> "I wondered," she says. "It wasn't like Bobby to ignore us." To ignore *her*, she means. I can see myriad emotions warring within her, but the one that triumphs is relief, and at this my heart sinks even further. At last she says, "Are you going to tell me why?"
>
> "I was afraid," I explain, but I can see she doesn't understand, and I'm visited by an unwanted memory of the day I peered in through the smoky window of the passenger train and saw on Sarah's lap the drawing she'd done of Bobby, the same one she alluded to in her postscript [to the letter]. I knew immediately what it meant, but in a heartbeat I'd hidden both the drawing and its significance away where it would trouble me no further. I think I've remembered it no more than half a dozen times in all the years since.
>
> "Afraid you'd fall in love with him," I manage to tell her. "With Bobby. Again."

Suppose one was physically present as a side participant as these events unfolded. Side participants, of course, would not have access to Lou's stream of consciousness. However, the revelations made through the characters' language—by which side participants would be duly informed—provide a context for a range of mental responses. Side participants could respond both to local details of the events and to the more global situations. At a local level, they might think "How dare he [steam open the envelope]!" or "You were right to be afraid!" At a more global level, they might look into the couple's future and offer mental advice to Sarah such as "Stand by Lou!" or "Leave him and get on with your life!" We call these types of mental content *participatory responses* (Allbritton & Gerrig, 1991; Polichak & Gerrig, 2002).

As we argued earlier, participatory responses emerge from the cognitive processes people regularly engage as side participants. However, to give a full account we need to provide a generalization of Clark and Carlson's original theory (cf. Clark, 1996). In many narrative circumstances, again in parallel to real-life circumstances, readers experience actions as side participants. Consider this moment from *Bridge of Sighs*: "Back at the studio, Noonan saw the mail had arrived, so he brought it upstairs and tossed it and the Columbia envelope onto the table next to his bed" (p. 43). Noonan did not perform his actions on behalf of the reader. Nonetheless, the reader has encoded and might mentally respond to the actions. We suggest, as such, that readers function as side participants with respect both to characters' language and to characters' actions.

As may be clear from the examples we have provided so far, it is likely to be quite difficult to specify, for a narrative of any complexity, exactly what participatory responses readers will encode. In that sense, the participatory perspective calls attention to an important type of individual differences among readers. Previous research has focused on cognitive differences among readers (e.g., their reading ability or their working memory capacity) or knowledge differences (e.g., the background experiences they bring to texts) (e.g., Chiesi, Spilich, & Voss, 1979; Kendeou & van den Broek, 2007; Long, Johns, & Morris, 2006). Consider the scene we quoted in which Sarah informs Lou about some of the facts of Venice. We would expect that readers who have visited Venice might already be familiar with "aqua alta" and "calles" and therefore have a different experience of this interchange than Venice naïve readers. However, we also suggested that readers with Venice experience would have an extra way to participate in this scene—by encoding responses to Lou's questions. Thus, if we were to provide a precise account of readers' moment-by-moment experiences, we would find differences both in the memories that they were able to retrieve and the participatory uses to which they put those memories.

More generally, readers bring different lifetimes of experiences to every moment of a narrative. We suspect that individual differences will become even more evident as narrative events become more controversial. We have suggested, for example, that readers might have diametrically opposed responses to Lou's revelation that he steamed opened Sarah's letter to Bobby Marconi (i.e., "Stay!" or "Go!"). In this instance, we expect those different participatory responses to arise from the details of readers' own romantic involvements. *Bridge of Sighs* also has much to say about the relationships between parents and children. Given each reader's unique experiences of those relationships it seems likely that no two readers would experience the novel in exactly the same way.

Note also that readers' participatory responses are likely to differ with respect to the specificity of their content. If, for example, readers respond to Lou's confession that he steamed open the envelope, the response might be a nonspecific emotional response—something like an "Oh no!" rather than something as precise as "How dare he!" In some circumstances, readers may encode participatory responses through automatic processes. Suppose a text provides an episode in which a child is about to run into a street. If that scene makes contact with a sufficient number of representations in readers' memory, we might expect that strategic reflection would be unnecessary for "Don't!" to emerge as a participatory response. However, we suspect that the majority of readers' participatory responses—and therefore the specificity of those responses—will largely be under strategic control. This analysis provides an additional reason to assert that it would not be possible to predict exactly what participatory content readers would encode. (However, we review research later in the chapter that suggests, whatever the precise content, participatory responses affect readers' moment-by-moment narrative experiences.)

We have suggested that readers often encode participatory responses that have the same mental status as responses they would encode were they real-world side participants. To bolster that analysis, we make a brief detour into research from social psychology.

2.3. Actors, Observers, and Participants

One of the classic distinctions social psychologists make is between actors and observers: Actors perform behaviors while observers watch. These different roles matter because, for example, actors and observers often come to rather different causal analyses of the same situation (at least in Western cultures; see Menon, Morris, Chiu, & Hong, 1999). In particular, actors tend to make more situational attributions about the roots of their behavior whereas observers tend to make more dispositional attributions (Ross, 1977). For example, in one scene from *Bridge of Sighs*, Robert Noonan and his art dealer are discussing Noonan's reluctance to return from Venice to the United States for the opening of a new show. For Noonan, the cause rests in the situation: He feels productive in Venice and does not wish to deal with the hurly-burly of New York City. However his dealer makes a dispositional attribution, "Your problem," Hugh said,. . . "is that you think selling's beneath you" (p. 53).

Researchers have provided several classic demonstrations of the different causal analyses of actors and observers. For example, Storms (1973) had two people engage in a conversation while two other people watched. Storms also made two videotapes of the conversation, one from the perspective of an actor and a second from the perspective of an observer. At the end of the conversation, the actors and observers made attributions about four dimensions of the actors' behavior (friendliness, talkativeness, nervousness, and dominance) with respect to their origin of that behavior in personal characteristics or situational forces. Observers were more likely to make dispositional attributions. However, when participants viewed a videotape that encouraged them to take the opposite perspective (by, e.g., showing the actor the conversation from an observer's point of view) the pattern of attributions shifted to match the new perspective.

Theorists have sometimes attempted to draw upon such actor–observer differences to test an account of readers as observers. They have argued, for example, that different types of narration (i.e., first person vs third person) might make readers experience scenes more as actors or observers with consequences for how they assess causal forces in narrative episodes (see Gerrig, 1993). However, researchers' attempts to change readers' causal analyses of scenes by shifting perspective have not been consistently successful (e.g., Fiske, Taylor, Etcoff, & Laufer, 1979). The participatory perspective suggests why the likening of readers to observers is flawed: The perspective suggests that readers are not observers—they are, instead, side participants. They are not quite actors, of course, but they nonetheless are engaged with events in ways that observers are not.

The social psychological literature provides documentation of the cognitive involvement of side participants. Consider a project by Pronin, Wegner, McCarthy, and Rodriquez (2006) that addressed what the researchers termed "everyday magical powers" (p. 218). In one experiment, the researchers approached 67 Princeton fans at a basketball game between Princeton and Harvard. The Princeton fans completed one of two surveys that the researchers intended to affect the thoughts participants had as the game unfolded. In the *player contribution thoughts* condition, the researchers asked the fans to contemplate seven Princeton players with respect to the contributions they were likely to make to the team's play during the game. In the *player identification thoughts* condition, the researchers asked the fans to contemplate how the same seven players might be identified in a crowd. The researchers predicted that the fans "would feel more responsible for the outcome of the game if they had, before the start of it, entertained outcome-relevant thoughts about how each player could contribute to the game" (p. 225).

To test that prediction, the experimenters approached each participant during a time out and asked him or her to complete a series of questions. Among those questions were those that assessed participants' feelings of responsibility (e.g., "How responsible do you feel for how the players are playing so far?" and "Up to this point, do you feel like you have affected how the players have performed?"). The participants who had contemplated the player's likely contributions reported bearing more responsibility than those who only contemplated how best to identify the players.

These results emerged because the participants who encoded player contribution thoughts responded as if those thoughts had some impact on the events that subsequently unfolded. We claim, similarly, that readers who encode participatory responses experience narrative events as if they bear some responsibility for the events that ensue. More generally, we suggest that this type of social psychological research supports our contention that the responses readers encode as side participants give them the sense that they are more than merely observers of narrative events.

2.4. The Participatory Perspective and Canonical Text Processing Theories

On the whole, theories of text processing have concerned themselves with the different types of representations at which readers arrive as they progress through a text. In classic early work (Kintsch & van Dijk, 1978; van Dijk & Kintsch, 1983) outlined the processes through which readers proceed from a text's basic propositions (i.e., the basic units of meaning) to arrive ultimately at a situation model. A situation model is "a mental representation of what [a] text is about": A representation of "the people, objects, locations, events, and actions described in a text" (Zwaan, 1999, p. 15). Abundant research effort has been devoted to understanding the cognitive processes that yield situation models and the content of those models (Zwaan & Radvansky, 1998).

Because situation models encode richer information than "the words, phrases, clauses, sentences, and paragraphs of a text" (Zwaan, 1999, p. 15), researchers have also frequently concerned themselves with the question of how and when readers interpolate information into their representations—inferences that were not directly present in the text. The study of inference-making is among the oldest enterprises in psycholinguistics. Researchers have devoted considerable effort to the goal of specifying what inferences readers encode and with what time course (for reviews, see Guéraud and O'Brien, 2005).

The participatory perspective on narrative experiences does not stand in opposition to these major strands of research. Rather, it calls attention to types of reader experiences that have been missing from these canonical analyses. Participatory responses are a different type of content than, for example, the propositions readers recover from a text or the inferences with which they enlarge their situation models. Consider the claim that readers would encode mental advice such as "Run away! Escape!" as they read the *Bridge of Sighs* scene in which Lou has been snatched by Jerzy and his gang. These responses likely arise because readers have a sense of impending doom. That sense of impending doom is almost certainly the product of inferential processes. That is, readers likely retrieve instances from their world knowledge that suggest that situations of this type rarely lead to happy outcomes. Readers might infer that Lou should try to escape. However, the actual content of that advice (whether it manifests itself as "Escape!" or "Run away!" or anything else) does not just fill a gap in the text.

The goals of canonical text processing theories have been to specify both readers' moment-by-moment processes as they experience narratives and the representations that result from those processes. The research we describe in later sections of this chapter suggests that the participatory perspective has important implications for those goals. If, in fact, readers encode participatory responses, theories need to enlarge their account of moment-by-moment processes and readers' subsequent representations. We believe the research we review makes a strong case for reader participation and, as such, makes the equally strong case that canonical theories of text processing are too narrow in their scope.

However, the participatory perspective provides an additional challenge to canonical theories. Earlier we argued that readers' participatory responses are likely to be idiosyncratic. This acknowledgement of individual differences suggests why it may remain awkward for proponents of canonical theories to integrate readers' participation into those theories. First, canonical theories have largely focused on readers' automatic processes—what texts compel readers to do. However, as we have emphasized, most reader participation is voluntary in the same way that real-world participation is voluntary. We would expect different readers to expend different amounts of strategic effort depending, for example, on how compelling they found the events narrated in particular texts. In that sense, we can make a process statement (i.e., "Here's what it means to participate") but can give no clear statement of products (i.e., "Here's a representation of the text at which all competent readers will arrive"). Thus, the participatory perspective suggests that the goal of precisely specifying readers' representations cannot be achieved. If situation models include readers' participation-driven assessment of narrative events, those models will be different for each reader.

In this section, we have outlined the major features of the participatory perspective. In the remaining sections of the chapter, we describe research that has emerged from this perspective. We use excerpts from *The Bridge of Sighs* to illustrate how our research agenda emerges from readers' ordinary narrative experiences.

3. Readers' Preferences

Throughout *Bridge of Sighs*, Sarah's father, Mr. Berg, has been working on a novel. In fact, every summer Sarah goes to live with her mother (her parents are divorced) so that her father (a school teacher) can spend the entire summer working on his book. Finally, Mr. Berg's novel is complete (p. 514):

> According to Sarah, her father submitted the book in early January to a handful of New York publishers—only the best houses of course and their best editors, men already associated with the likes of Hemingway, Fitzgerald, Faulkner and Ellison—and had immediately commenced racing through the mail every day.

The situation permits two general outcomes: Mr. Berg's novel will be accepted or it will be rejected. The clarity of the situation makes the moment rife with opportunities for readers to function as participants. In particular, we would expect readers to encode preferences for the outcome that will obtain. The expression of those preferences (i.e., the content of readers' participatory responses) will depend on readers' own life experiences. To what extent have they known people like Mr. Berg? Do they wish positive or negative outcomes to accrue to such an individual?

As it happens, rejection letters start to arrive about two months after Mr. Berg submitted the manuscript. The narration of those rejections is the same for all readers. That is, readers all experience the same text. We suggest, however, that the way in which readers assimilate those outcomes will differ as a function of the preferences they encoded. Those readers who encoded the preference that Mr. Berg succeed might find it literally more difficult to read the text. Those readers who hoped that Mr. Berg would fail should find the novel's subsequent episode relatively easy to absorb. Consider how Mr. Berg responds to the first pair of rejection letters (p. 515):

> Since he'd sent the manuscript off, an even better ending had occurred to him, so he sat down and composed a letter for all the remaining editors, outlining the new ending and explaining why he thought it might conceivably be an improvement over the old, though of course he'd understand if they were wedded to the original.

We would imagine that readers who wished Mr. Berg to succeed would have a very different response to this account of his actions than would those who wished him to fail. We might expect people to respond "That could work!" versus "What a loser!" Consider the novels' next sentence: "This letter's only immediate effect was to generate another form rejection." Readers who continued to hope for Mr. Berg's good fortune should experience this sentence as a strong mismatch to their preferences. We would expect them to find it relatively difficult to assimilate this outcome to their discourse representation. We now describe a pair of projects that explicitly tested this analysis of reader participation.

3.1. Readers' Preferences in the Context of Time Shifts

As *Bridge of Sighs* unfolds, Russo provides time shifts in the narrative that range from minutes to years. Single sentences, for example, move the action forward a portion of an hour (e.g., "It took my mother about twenty minutes to stop shaking after Father Gluck had left," p. 144) or by 24 hours (e.g., "Mr. Marconi's fury had not diminished a jot the next day," p. 88). Research on text processing suggests that the internal structure of readers' situation models is sensitive to the relative magnitude of time shifts (e.g., Ditman, Holcomb, & Kuperberg, 2008; Speer & Zacks, 2005).

For example, Zwaan (1996) had participants read brief stories that varied with respect to the size of a time shift (e.g., *a moment later*, *an hour later*, or *a day later*). The size of the shift affected the accessibility of story concepts that preceded the time shifts: Concepts were relatively less accessible after the longer time shifts. Results of this sort provide evidence for the *event-indexing model* which suggests that time is among the narrative dimensions that readers diligently encode into their situation models (Zwaan, Langston, & Graesser, 1995; Zwaan, Magliano, & Graesser, 1995).

If readers are attentive to narrative time shifts, we might also expect them to exploit world knowledge to constrain their inferences about what events can transpire given a particular time shift. Recall that after Mr. Berg's submission of his manuscript he "had immediately commenced racing through the mail every day." Readers who know something about the mechanics of manuscript submission will understand that the probability of a swift response is quite low. In fact, they would likely be quite surprised had a response arrived in just a few days. Still, suppose those same readers preferred that an acceptance (or rejection) come swiftly. They might join with Mr. Berg in his unlikely expectations. If, for example, readers encoded a participatory response such as "I hope he hears soon," they might find it easy to absorb information that would otherwise disconcert them.

Rapp and Gerrig (2002) sought to demonstrate the impact of readers' preferences on their experience of time shifts. As a first step, they needed to establish that, in the absence of preferences, readers are sensitive to which outcomes could plausibly transpire in a certain period of time. Table 1 provides an example of one of their 24 experimental stimuli. For each story, participants read a version that ended with either a minute time shift or an hour time shift. In the initial experiment, participants made explicit judgments about what was likely to happen next in the story. They might, for example, have read the sentence "Paul kept screwing up lines" and responded either "yes" or "no." Rapp and Gerrig predicted that participants' responses would demonstrate sensitivity to the match between time shifts and outcomes. The data supported that prediction. Participants agreed that an outcome "would happen next" 85% of the time when the time shift and outcome matched but only 28% of the time when there was a mismatch.

In a second experiment, Rapp and Gerrig sought converging data from a second measure. Participants read stories that included the outcome sentences (yielding four versions of each story). The experiment asked participants to push a button to indicate that they had understood each sentence. For reading times, Rapp and Gerrig predicted that participants would find it more difficult to assimilate outcomes to their discourse representations when an outcome was inconsistent with a time shift. The data supported

Table 1 Sample Story from Rapp & Gerrig (2002).

Paul was a part-time actor and model who posed for advertisements and had done some work on television.
Preference material
Paul refused to sign autographs for his fans, saying "I don't like their dirty hands touching my beautiful clothing" (minute-consistent preference).
Paul was humble, spending many hours signing autographs for his fans even when it prevented him from eating dinner (hour-consistent preference).
Paul was going to star in a soap opera.
He had been hired to work on a show called "The World We Love."
When Paul first arrived at the studio, the director handed him his lines and showed him his dressing room.
The director's assistant mentioned that the teleprompter was not operating properly and that he would have to memorize all his lines.
In his first scene, he was supposed to meet the lead female character at a diner and has a conversation about several of the other personalities in town.
Paul sat down in a chair to learn his lines.
Time shifts
A minute later the producer came in and told him "You're on now!" (minute time shift)
An hour later the producer came in and told him "You're on now!" (hour time shift)
Outcomes
Paul kept screwing up lines (minute-consistent outcome).
Paul gave a flawless performance (hour-consistent outcome).

Note: In the initial experiments, participants read stories that excluded the preference information. For those experiments, there were four versions of each story (with two time shifts and two outcomes). For the experiments that included preference material, there were eight version of each story (with two preferences, two time shifts, and two outcomes).

that prediction. When an outcome mismatched a time shift, participants took 140 ms longer to read the outcome sentences.

With this demonstration in hand, Rapp and Gerrig supplemented each story with additional text that they intended to make participants prefer either the minute-consistent outcome or the hour-consistent outcome (see Table 1 for examples). The general intent was for this new material to function as impetus for participatory responses. In that way, readers would explicitly encode (to some degree of specificity) preferences with which the ultimate outcome could match or mismatch. As we noted earlier, we generally expect readers to express different preferences (as a function of their own life histories) with respect to narrative outcomes. However, for the purpose of their experiments, Rapp and Gerrig needed to ensure that a solid majority of readers would encode the same preferences in response to the experimental texts. In a norming study, participants read a version of each experimental story with one or the other lines of preference material. Each story ended with both possible outcomes. Participants rated which outcome they preferred. The norming study confirmed that the preference material successfully prompted readers to favor either the minute- or hour-consistent outcome.

As before, Rapp and Gerrig conducted a pair of experiments. In the first experiment, participants provided "yes" or "no" responses to particular outcomes. Overall, participants were still sensitive to the likely concomitants of time shifts. Participants accepted outcomes that matched the time shift 35% more often than they accepted those that mismatched. However, readers' preferences also wielded an influence on their responses. Participants accepted outcomes that matched their preferences 17% more often than they accepted those that mismatched. Consider circumstances in which the stories ended with the minute time shift (e.g., "A minute later the producer came in and told him 'You're on now!"). In the absence of a particular preference, participants agreed with the minute-consistent outcome (e.g., "Paul kept screwing up lines.") 86% of the time. However, when participants read stories that created a preference for an hour-consistent outcome (e.g., when participants read that Paul was generous to his fans), they agreed with the minute-consistent outcome only 69% of the time.

Participants' reading times yielded much the same pattern. The data still revealed an overall impact of the match between time shifts and outcomes. Participants' took 220 ms longer to read outcomes that were inconsistent with the time shifts. However, readers were also slowed by 302 ms when the outcome mismatched their preferences. As a whole, this series of experiments supports the claim that readers' preferences have an impact on how they experience narratives. Those preferences operate even in the domain of time shifts, where outcomes are greatly constrained by the literal passage of time.

3.2. Readers' Preferences in the Context of Judgments About Outcomes

Rapp and Gerrig (2006) undertook a second project to provide additional evidence that readers' preferences have consequences for narrative experiences. This second series of experiments assessed the impact of readers' preferences on what they believe lies in characters' futures. The earlier project created a tension between what readers knew could happen given a particular interval of time and what they wished could happen in that same interval. The second project created similar tension between outcomes readers thought were likely and those they preferred. Once again, we can draw out the relevant contrast from Mr. Berg's submission of his novel. Readers with appropriate knowledge will know that the prior odds that publishers will accept a novel for publication are quite low. In addition, *Bridge of Sighs* provides scant evidence that Mr. Berg is anything but delusional about his own talent. Thus, readers should have little reason to expect anything but a rejection. Still, many readers are likely to hope that Mr. Berg will succeed. They can encode the participatory response "I hope the book will be accepted" even given the long odds against that outcome. In parallel to the findings for passages of time, Rapp and Gerrig expected readers to have more difficulty accepting and assimilating outcomes that mismatched their preferences.

When examining readers' predictions about narrative outcomes, text processing research has been focused on defining the circumstances in which readers encode *predictive inferences* and the content of those inferences (e.g., Casteel, 2007; Cook, Limber, & O'Brien, 2001; Peracchi & O'Brien, 2004). The particular goal has been to define which inferences readers encode as the product of automatic processes. Consider this brief text (McKoon & Ratcliff, 1986):

> The director and cameraman were ready to shoot close-ups when suddenly the actress fell from the 14th story.

Using a variety of tasks, McKoon and Ratcliff (1986) demonstrated that readers automatically encode a predictive inference along the lines of "something bad will happen" rather than the more specific inference "the actress will die." Subsequent research has attempted to define the elements of narrative contexts that determine when readers encode more specific inferences such as that a waitress will *dump* a plate of spaghetti on the head of a rude customer (Guéraud, Tapiero, & O'Brien, 2008).

Given that readers show a predilection to look into characters' future, the question asked by Rapp and Gerrig (2006) was how readers' preferences interact with those predictions. Suppose the actress falling from the balcony is renowned for her charity work. Would readers find it more difficult to accept a particular outcome (e.g., "The actress died instantly when she hit the ground.") than if she were known to be abusive and dishonest? The 24 stories Rapp and Gerrig wrote allowed such explicit contrasts between likely outcomes and what readers might prefer. Consider the example in Table 2. In the *success bias* version of the story, Peter has a very powerful poker hand (four kings). In the *failure bias* version of the story, Peter has a "pretty lousy hand." Participants in a first pair of experiments read versions of the story that had one or the other bias and arrived at outcomes that communicated either *success* or *failure*. The four versions of each story provided matches or mismatches between the contextual biases and the outcomes. For example, participants might have read that Peter had a "pretty lousy hand" but that, nonetheless, "Peter won the pot."

Table 2 Sample Story from Rapp & Gerrig (2006).

Preference material
Peter was trying to raise money to pay for his sister's college education (success preference).
Peter was raising money to finance a racist organization in the United States (failure preference).
Peter was hoping to win lots of money at the poker tables in Vegas.
Contextual bias
He was holding the best hand he had seen in weeks: four kings (success bias).
He was holding a pretty lousy hand but stayed in the game (failure bias).
Peter bet all of his money on the current hand.
Then he and his opponent revealed their cards.
Outcomes
Peter won the pot of money with his hand (success outcome).
Peter lost the hand and all of his money (failure outcome).

Note: In the initial experiments, participants read stories that excluded the preference information. For those experiments, there were four versions of each story (with two contextual biases and two outcomes). For the experiments that included preference material, there were eight version of each story (with two preferences, two contextual biases, and two outcomes).

In a first pair of experiments, Rapp and Gerrig confirmed that readers were sensitive to the contextual biases. One experiment asked participants to accept or reject a particular outcome as what they thought would happen next. When an outcome was consistent with the contextual bias, participants were 60% more likely to agree that the outcome would obtain. A second experiment asked participants to push a button to indicate that they had understood each sentence including the outcome sentence. When outcomes were consistent with biases, participants took 203 ms less time to read the outcome sentences. These data suggest that readers were reasonably sensitive to contextual biases when they read narrative outcomes.

The second pair of experiments gauged the impact of readers' preferences. As exemplified in Table 2, one version of each story included material that Rapp and Gerrig intended to create preferences toward the characters' success whereas the other version instilled the opposite preference. Rapp and Gerrig carried out a norming study to ensure that the new material had the intended effect on readers' preferences.

As with the project on time shifts, Rapp and Gerrig expected that, whatever their preferences, readers would remain sensitive overall to the base rates implied by the contextual biases. This proved to be the case. When readers provided explicit judgments of whether they thought a particular outcome would obtain (e.g., ‘‘Peter lost the hand and all of his money.'') they were 44% more likely to agree with outcomes that matched the story's success or failure bias. However, against that background, participants agreed with outcomes that matched their preferences 19% more often. Consider stories in which participants judged successful outcomes (e.g., Peter won the pot of money with his hand) when the context also was biased toward success (e.g., Peter's hand was four kings). When participants also had a preference for the success outcome, they responded ''yes'' to the success outcome 95% of the time. However, when participants' preference was for the failure outcome, their agreement rate fell to 69%. A final experiment with reading times generated the same conclusions. When outcomes mismatched the story's success or failure bias, participants were 184 ms slower to read the outcomes. However, they were also 96 ms slower to read outcomes that mismatched their preferences.

This pair of projects emerged from the participatory perspective: They document that readers' responses—the preferences they encode—have an impact on the way they experience a narrative. More generally, the participatory perspective poses the question, ''How would real-world participants respond in this situation?'' The next project we describe represents another answer to that question. We assess the extent to which readers weigh in on characters' decisions.

4. Readers' Participation in Characters' Decisions

In one episode from *Bridge of Sighs*, Lou must make two decisions in quick succession. He is minding his parents' convenience store when a girl on whom Lou has a serious crush, Karen Cirillo, enters. After some brief exchanges about books, Karen comes to the purpose of her visit (p. 184):

> ''How about a pack of Parliaments?'' she said, nodding at the cigarette counter behind me. Again I hesitated. She wasn't old enough to buy cigarettes any more than I was old enough to sell them, and my father was strict about minors.

This situation calls for Lou to make a decision: Will he sell Karen the cigarettes or not? At this point in the novel, readers have gained insight about why Lou could make either decision. Being well-informed side participants, it is likely that readers will weigh in. Readers might think, ''Your dad won't find out, and Karen will really appreciate it,'' or ''It's not worth it!'' If some readers give Lou the mental advice to refuse Karen's request, they will be disappointed because he eventually lets her have the cigarettes. However, those same readers will not be surprised that Lou's decision turns out poorly. A few moments later, Karen's intimidating boyfriend, Jerzy Quinn, enters the store. Karen defends Lou to Jerzy in a way that requires him to make an additional decision (p. 188):

> "Lou's nice. He gave me a pack of cigs," Karen said, smiling at me now, challenging me to say the cigarettes hadn't been a gift, that in my father's store we didn't hand out free cigarettes or free anything.

Again, readers have the opportunity to participate in the scene by mentally weighing in on Lou's decision. As before, Lou makes a decision that will likely contradict some readers' mental advice. Lou lets Karen have the cigarettes for free. That decision has negative consequences in both the short- and long run. In the short run, Lou has a moment of panic when his father enters the store just as Karen and Jerzy are leaving: He wonders if his father counted the packs of cigarettes before he went home for dinner. In the long run, Karen continues to expect (and obtain) free packs of cigarettes, to Lou's growing discomfort. For readers who wanted Lou to obtain money from Karen, both of these outcomes should be easy to assimilate. If, however, a reader believed giving in to Karen's request was acceptable, it may be relatively more difficult to assimilate the resulting negative outcomes.

In everyday life, people are often called upon to provide advice on decisions of various import. For example, in a scene from *Bridge of Sighs*, Bobby needs to decide when to break up with his girlfriend. Sarah provides unambiguous advice: "Not tonight" (p. 529). As with other types of language use, people are often cast in the role of side participant when advice is sought. Real-life side participants for the conversation between Bobby and Sarah would likely encode advice as well (which might or might not concur with "Not tonight"). We believe that side participants will often act as if they did, in fact, offer their advice when the time comes to assess the consequences of the decision. To return to our earlier example, we suggest that readers who encoded advice for Lou along the lines of "Don't give her the cigarettes" might very well think, "I told you so!" when matters don't turn out well. Our experiments attempted to capture moments of that sort. We tested the claim that readers find it easier to assimilate outcomes if there is a match between their preference for a character's decision and the eventual outcome.

As we noted earlier, we expect that readers' participatory responses will arise from their own real-world experiences. For that reason, we would expect that different readers would offer different mental advice in the same narrative circumstances. To test the consequences of those individual differences, we added another dimension to our initial experiment: We created separate groups of stories for which there was either relatively high or relatively low reader agreement on the wisdom of characters' decisions. To construct these groups, we conducted a norming study with a pool of 30 stories. We asked participants to read the introduction to each story and indicate which of two decisions they felt the character should make. This provided a measure of which decision was more popular. Based on participants' responses, we selected 12 for which participants had relatively high agreement (on average, the popular decision was selected 83.3% of the time) and 12 for which participants had relatively low agreement (on average, the popular decision was selected 63.5% of the time).

Note that we asked participants to indicate what they thought the character should do rather than what they, themselves, would do in a comparable situation. Research suggests that people tend to be more conservative when they take the side-participant role. Consider a study by Fernandez-Duque and Wifall (2007) which examined differences in decision making between actors and (so-called) observers. The actors played a simple card game in which there were nine good cards and one bad card: For each good card flipped over, the actor would win one dollar, but if the bad card was flipped over, the game would end and the actor would win no money. Observers watched an actor play the game and indicated whether they thought the actor should flip the next card. Actors made riskier decisions (i.e., they opted to flip more cards) than observers thought was prudent: On average, observers would have advised actors to stop sooner. Although Fernandez-Duque and Wifall use the term "observers," for us that group counts as participants. That is, they were mentally involved as the task unfolded and, presumably, also encoded thoughts such as "I told you so!" or "Good decision!" Our norming study followed this lead by asking participants to report the decisions that the characters should make.

Table 3 provides examples of both high and low agreement stories. For the top example, a large majority of readers agreed that Pam should decide to drop off her paper right away. The table also provides two possible outcomes: Either the professor decided to penalize late papers or he did not. Note that these outcomes are out of Pam's control. That is, her decision does not change the likelihood that either outcome will obtain. However, suppose she opted to drop off her paper right away. One outcome (i.e., the professor shows no mercy) is positive given that decision (because if she had waited, she would have been penalized); the other outcome (i.e., the professor is forgiving) is negative (because she made an unnecessary midnight drive to school). If Pam had made the opposite decision, the positive and negative outcomes would be reversed.

For the bottom example in Table 3, a slimmer majority agreed that David should decide to squeeze into his suit. Again, two outcomes are possible (i.e., other people dressed formally or casually) that are out of David's control. Again, what readers will interpret as a positive or negative outcome depends on the decision that preceded it.

For the final pool of 24 items, we conducted a second norming study to ensure that participants believed that the outcomes were roughly equally likely. Participants read each story until they reached the outcome sentence

Table 3 Sample Story from Jacovina & Gerrig (2008).

High agreement story
Pam finally finished her term paper that was due by 12 midnight.
When she tried to submit it online, however, the course Web site was not working.
It would take almost an hour to drive to school to drop it off before 12.
She could instead wait and put it in her professor's mailbox the next morning when she went to school.
Decisions
Pam decided to drop it off right then, prior to midnight (popular decision).
Pam decided to turn it in at school the following day (unpopular decision).
The next night, the professor sent an email addressing the fact that the Web site had been down.
Outcomes
It said late papers would be penalized no matter what.
It said that late papers would therefore not be penalized.
Low agreement story
David was getting dressed for his niece's sweet 16 party.
The invitation did not mention a dress code, but he knew her parents were dressing up.
He rarely dressed formally and knew his suit would be tight and uncomfortable.
While he preferred to dress casual, he did not want to be the only one underdressed.
Decisions
David chose to squeeze into his suit despite the restricted fit (popular decision).
David chose to dress casual, with a polo shirt and khakis (unpopular decision).
Once at the party, he greeted his family members.
Outcomes
He saw that with a few exceptions, they were formally dressed.
He saw that with a few exceptions, they all dressed casual.

Note: Participants read one of four versions of each story (with two decisions and two outcomes).

at which point they saw both possible outcomes. Participants used 9-point scale to indicate which outcome they believed would occur and how strongly they felt about their response. (They could also circle 5 to indicate that both outcomes seemed equally likely.) We recoded the data so that a response of 1 meant that participants thought a matching outcome (e.g., a positive outcome after a popular decision) was likely and 9 meant that participants that the same outcome was unlikely. The average ratings for the high and low agreement stories were 4.58 and 4.52, respectively. These norming data suggest that any differences in readers' responses to the two types of stories do not reflect differences in the likelihood of the stories' outcomes.

In our initial experiment, we asked participants to read the stories one sentence at a time. They read one of the four versions of each high and low agreement story, which contrasted on the popularity of the outcome (popular vs unpopular) and the valence of the outcome (positive or negative with respect to the prior decision). We recorded participants' reading times for each sentence. For the high agreement stories, we expected that participants' reading times would be longest when the outcome mismatched the decision. When, for example, the character made an unpopular decision that was nonetheless followed by a positive outcome (with respect to that decision), we expected readers would find that outcome hard to assimilate into their discourse representations. For the low agreement stories, we did not expect consistency among the participants' responses to the characters' decisions and, therefore, did not expect to find a consistent impact on participants' assimilation of the outcomes. The data supported our predictions. For high agreement stories, participants read the outcome sentences 508 ms faster when the outcome matched the decision. For low agreement stories, participants actually read the matching outcomes 130 ms slower.

These data provide strong initial evidence that readers' responses to characters' decisions affect how they assimilate the outcomes that follow those decisions. However, the results rely on the overall popularity of decisions we derived from our initial norming study. In a second experiment, we interrupted each participant after he or she arrived at the moment in the story at which the character needed to make a decision. We explicitly asked participants to indicate what they thought the character should do. (They could also indicate that they had no preference.)

This procedure provides a less natural way to experience a narrative, but it allowed us to categorize each story as matching or mismatching for each individual reader. We expected that the data from this procedure would converge with our earlier findings. We no longer have the distinction between popular and unpopular stories. Instead, we expect that readers would find it harder to assimilate whichever outcome was discordant with their own personal report of the decision that they preferred the character to make.

To analyze the reading time data, we used readers' own responses to sort each story into favorable decisions (stories for which the character's decision was consistent with the participant's preference) and unfavorable decisions (stories for which the character's decision was inconsistent with the participant's preference). Based on this sort, we determined which outcomes counted as matching for each story. As we expected, participants took longer to read, by 266 ms, the outcomes that mismatched the decisions they preferred. Thus, when readers believed that David should dress casually for his niece's sweet sixteen, and David did dress casually in the story, readers took longer to assimilate the outcome in which all his family members were formally dressed. This is because a negative outcome is a mismatch to what they believed was a good decision.

Taken together, these data support our prediction that readers participate in characters' decisions. We suspect that each relationship between decisions and outcomes leads readers to a different mental response. We noted earlier that readers might think "I told you so!" when characters fail to heed readers' (mental) advice. Similarly, readers might revel in their own acumen as advice givers when characters follow their advice and things go well; readers might experience guilt when characters follow their advice but the outcome is negative with respect to the decision (cf. Gerrig & Prentice, 1996). We suggest, more generally, that readers' responses to characters' decisions represent a particular rich opportunity for participation.

5. Readers' Responses to Mysteries

As with many novels, *Bridge of Sighs* begins by hinting at revelations that lie in the readers' future (p. 3):

> First, the facts.
>
> My name is Louis Charles Lynch. I am sixty years old, and for nearly 40 of those years I've been a devoted if not terribly exciting husband to the same lovely woman, as well as a doting father to Owen, our son, who is now himself a grown, married man. He and his wife are childless and likely, alas, to so remain.

This brief excerpt provides some mysteries (e.g., What makes Louis "not terribly exciting?" Why are his son and daughter-in-law childless?) that readers might expect the subsequent text to address. Our question is how readers respond when these questions first arise. One possibility is that they represent the information in the text without taking note of the mysteries it presents. However, the participatory perspective suggests that readers would attend to these mysteries as if they were real-world side participants. For example, were a speaker to reveal this same information in a conversation, it seems likely that a side participant would encode a question such as "Why are his son and daughter-in-law childless?" If the speaker were being cooperative, certainly that information should be forthcoming (Grice, 1975). By formally encoding such mysteries when they first arise, side participants (in real-life and as readers) are prepared to assimilate the mysteries' solutions. In this section, we describe two empirical projects that address readers' responses to mysteries.

5.1. Small Mysteries

The mysteries in the opening paragraphs of *Bridge of Sighs* seem to call attention to themselves. However, texts also present more subtle gaps between what the narrator knows and what the reader knows. Consider this excerpt from the novel (p. 41):

> Noonan took the vaporetto over to the Zattere. There he went to an outdoor café, ordered a cappuccino and waited for it to arrive before opening the manila envelope from Columbia University that Hugh had thrust at him on his way out the door, identical to the one that had arrived that summer and he'd marked RECEPIENT DECEASED: RETURN TO SENDER.

This is the novel's first mention of Hugh. Given this prominent introduction, however, readers almost certainly suspect (correctly, as it turns out) that this will not be Hugh's last mention. In fact, Hugh plays a rather pivotal role in Noonan's life and, thus, in the novel.

The participatory perspective explains why readers should expect to learn more about Hugh. In a real-world conversation, side participants expect that speakers will design their utterances with appropriate attention to what information is in common ground (Clark & Carlson, 1982). If the speaker produces information that is not in common ground, side participants have a reasonable expectation that speakers would offer clarifying information. Thus, in a real conversation, a side participant would have strong expectations that the subsequent text will provide an answer to the question "Who is Hugh (with respect to Noonan)?"

Text processing research provides additional support for the claim that readers would expect Hugh to play an ongoing role in the novel. When characters are introduced by proper names, readers expect those characters to play prominent roles in stories (Sanford, Moar, & Garrod, 1988). Suppose, instead that Hugh had been introduced as "his art dealer" (i.e., suppose the sentence had read "that his art dealer had thrust at him"). Under those circumstances, readers would have weaker expectations that the story would continue to mention the character.

If readers expect the text to return to Hugh—and, in particular, to provide information about Hugh's function in the narrative world—what might the moment-by-moment consequences be? The prediction that emerges from canonical theories of text processing is that readers will integrate new information and then move forward in the text (e.g., Kintsch, 1988). On that view, "Hugh" should briefly be in the focus of readers' discourse representations but then fade quickly (or as quickly as any other discourse entity) as the text proceeds. By contrast, the participatory approach predicts that "Hugh" will remain relatively accessible in readers' representations until the text provides an answer to the tacit question, "How will Hugh function in this story?" This prediction emerges from the participatory perspective because, as we have noted, readers' expectations of future revelations is supported by their everyday experiences as side participants.

To test the account given by the participatory perspective, Gerrig, Love, and McKoon (2009) wrote a series of brief texts that introduced characters in the manner that *Bridge of Sighs* introduces Hugh. For the example in Table 4, Billy is the *focal character* whose function in the narrative world is,

Table 4 Sample Story from Gerrig et al. (2009).

Introduction
Unresolved
Linda needed some boxes carried to her car. She had packed up all her books to get them ready to move. Her coworker Joan stuck her head in, saw all the chaos, and asked, "What's up?" Linda said, "I'm waiting for Billy to help me with this mess." Joan replied, "Call me if you need some extra help."
Distal resolution
Linda needed some boxes carried to her car by the janitor. She had packed up all her books to get them ready to move. Her coworker Joan stuck her head in, saw all the chaos, and asked, "What's up?" Linda said, "I'm waiting for Billy to help me with this mess." Joan replied, "Call me if you need some extra help."
Proximal resolution
Linda needed some boxes carried to her car. She had packed up all her books to get them ready to move. Her coworker Joan stuck her head in, saw all the chaos, and asked, "What's up?" Linda said, "I'm waiting for the janitor Billy to help me with this mess." Joan replied, "Call me if you need some extra help."
Continuation
Linda looked at her watch to check the time. She suddenly realized that there must be a problem with the watch. At least 20 min had passed, and it still read 2:15 p.m.
Resolution
Role revealed
Linda heard some footsteps in the hall. Billy entered Linda's office and looked at the pile of boxes. Billy said, "You're not supposed to ask a janitor to do heavy lifting." Linda asked, "Couldn't you make an exception for me?"
Role not revealed
Linda had purchased the watch while she was on vacation in Hawaii. It had looked quite beautiful in the bright Hawaiian sun. However, she had regretted the purchase almost as soon as she arrived home. Now she would have an excuse to throw it away.

Note: Across experiments, participants read different versions of the story that included one introductory portion, the continuation portion, and one resolution portion.

apparently, known to Linda and Joan. There were three versions of each story. In the *unresolved* version, the story did not reveal the focal character's function in the opening portion. In the two *resolved* versions of the story, the story did reveal the character's function. In the *distal resolution* version, the text revealed the role (e.g., ''. . .by the janitor'') in the first sentence, in advance of the name in the third sentence. In the *proximal resolution* version, the text revealed the role directly before the name (e.g., ''the janitor Billy''). Gerrig et al. predicted that the locus of the resolution was unimportant: The focal character would remain relatively accessible in the discourse representation only when the characters' role remained unresolved.

Participants in the experiment read each story a line at the time. At some point, the story was interrupted by a test word. Participants attempted to respond as quickly as possible whether that word had appeared in the previous part of the story. For the 24 experimental stories, the test word appeared at the end of the continuation section which, as indicated in Table 4, was the same for all versions of the story. Gerrig et al. predicted that response times to the test word—the focal character's name—would be reliably faster when that character's function in the narrative world remained unresolved. The data confirmed that prediction. Participants made correct ''yes'' judgments about 50 ms more quickly for the unresolved stories than they did for both types of resolution stories. The two resolution stories yielded almost exactly the same response times.

In this initial experiment, the unresolved stories ultimately revealed the focal character's narrative function in the final, resolution portion of each story. To ensure that readers were not strategically adopting a ''wait and see'' strategy, Gerrig et al. replicated the effect with stories that never provided a resolution (see the *Function not Revealed* ending in Table 4). With those endings, participants were still a reliable 37 ms faster to respond that the focal character's name had appeared in the text when the character remained unresolved.

In a final pair of experiments, Gerrig et al. demonstrated that the focal characters' lingering prominence in the discourse representation had consequences for other concepts in the text. If readers apportion relatively more attention to the focal character that should yield a decrement in attention to concepts in the story that appear after the focal character. To test that hypothesis, Gerrig et al. had participants respond to probe words (such as ''mess'' in Table 4) that appeared in the stories after the focal character's first mention. Consistent with the hypothesis, participants took a reliable 29 ms longer to respond to the probe words when the focal character remained unresolved. Processing for words that appear before the focal character should not be similarly disadvantaged. To test this prediction, Gerrig et al. conducted a final experiment that used probe words that preceded the focal characters' introduction (such as ''boxes'' in Table 4). For those probe words, the difference between the resolved and unresolved stories was a nonreliable 6 ms.

This series of experiments supports the prediction that readers respond immediately to this particular type of mystery as their narrative experiences unfold. Until readers determine, for example, what role Hugh plays in the *Bridge of Sighs*, he should remain somewhat more accessible in their representations. We suggest that this pattern arises because readers are behaving as if they were genuine side participants. The shift of attention may be subtle but it has consequences for how readers experience subsequent information in the text (by making that information somewhat less accessible). In Section 5.2, we turn to a less subtle type of mystery.

5.2. Suspense

Over the whole span of *Bridge of Spies*, there is an enduring mystery: Will Sarah and Noonan (who began life as Bobby Marconi) manage a reunion after decades apart. Toward the end of the novel, the mystery becomes a proper instance of suspense as the possibility of a meeting is narrated in a fashion that feels directly out of a Hitchcock film (p. 621):

> But as [Noonan] reached the end of the platform the train began moving and he peered anxiously into each car as it creaked past, his heart, unused to such physical exertion, thudding in his chest, his breathing shallow now. He'd just about concluded they weren't aboard when he saw them coming toward him in the next-to-last car. If that was the same black girl from the gallery, and if the dark-haired woman in sunglasses beside her wasn't just a stranger who happened to be occupying the next seat. What was it Sarah had said about unlikely odds? But it *had* to be them for all of this foolish commotion to have any meaning, he thought, for the constellation to *be* a constellation not just a cluster of random stars.

This moment evokes suspense because the situation defines two outcomes (i.e., either Noonan has found Sarah or he has not) that immediately present two further outcomes (i.e., Noonan will be able to get on the train or he will not).

Most research on suspense has focused on defining the features of texts that create feelings of suspense and how feelings of suspense change over time (see Vorderer, Wulff, & Friedrichsen, 1996, for several reviews). The feature that appears to define suspense is uncertainty (but see Gerrig, 1989). Uncertainty, however, is not sufficient to give readers a satisfying experience of suspense. Ortony, Clore, and Collins (1988), for example, argued that suspense requires "a Hope emotion and a Fear emotion" (p. 131) in the presence of uncertainty among outcomes. On Ortony et al.'s account, readers experience suspense as Noonan reaches the train because they hope that he will find Sarah but they fear that he will not. (Readers will also experience suspense if their hopes and fears are reversed.)

The requirement that readers experience hope and fear toward outcomes already sounds a lot like participation. However, we suggest that there is another way in which readers participate in the experience of suspense. Consider how *Bridge of Sighs* continues after Noonan's possible sighting of Sarah. In the next paragraph, Noonan engages in some explicit problem solving: ''It was the girl who noticed him waving. Was it a look of recognition she gave him? Did she nudge the woman sitting next to her?'' (p. 621). As participants, readers can ask themselves the same series of questions. However, there is potentially more for them to do. If they prefer that Noonan and Sarah meet, readers may very well engage in some problem solving of their own to give Noonan mental advice about what he might do to get on the train. To participate in this situation means, in part, to engage processes of problem solving.

To test this account of readers as problem solvers, Gerrig and Bernardo (1994) created narrative versions of classic problem solving phenomena. Participants read texts that were based on a scene from Ian Fleming's first James Bond novel, *Casino Royale* (Fleming, 1954). In the scene, the villain Le Chiffre has captured Bond. Bond is being led to an unknown location when he makes the decision to try to escape. For their initial experiments, Gerrig and Bernardo created three versions of about a 300 word scene that differed only with respect to a fountain pen they introduced into Fleming's text. The manipulation occurred during a moment at which one of Le Chiffre's henchmen has grabbed Bond's foot mid-attack, knocking him down. The *no mention* version of the scene did not allude to a pen: ''As he crashed to the ground, Bond rolled agilely and, with a motion in which he took great pride, he righted himself with minimal damage.'' In the *pen-removed* version of the text, the pen entered the scene: ''As he crashed to the ground, Bond rolled agilely and, with a motion that he hoped went unnoticed, moved his fountain pen deeper into his breast pocket.'' Later in the story, Le Chiffre confiscates Bond's pen:

> Le Chiffre observed his assistant's work attentively. Then, as if reading Bond's thoughts, he crossed the room and snatched away Bond's fountain pen. ''Come, my dear friend,'' said Le Chiffre, ''Let's not waste time.''

In the *mentioned-not removed* version of the story, participants read the sentence in which Bond protected his pen but not the material in which Le Chiffre removed it.

Why might these different versions of the story have an impact on readers' experiences of suspense? If readers function as problem solvers, we would expect them to experience more suspense to the extent that the goal state they wish to achieve—in this case, presumably, that Bond not meet an untimely end—becomes more distal. Even though readers might not have a clear sense of what Bond could do with the pen, the very fact that he tried to retain it makes the pen seems like a potential avenue for escape.

When Le Chiffre removes Bond's pen, that action should make readers feel as if a solution path to the goal (i.e., Bond's safe passage from Le Chiffre) has been removed. As such, Gerrig and Bernardo predicted that readers who experienced the pen's mention and removal would report the most suspense.

The data confirmed that prediction. Participants reported their feelings of suspense on a 9-point scale ranging from 1 (*not very suspenseful*) to 9 (*very suspenseful*). Ratings for the *no mention* version (M = 3.43) were nearly identical to those for the *mentioned-not removed* version (M = 3.47). Ratings for the *pen-removed* version (M = 4.06) were reliably higher. This pattern of means supports the contention that readers were responding to the removal of the pen as if that action changed the structure of the solution space.

To examine further this conception of readers as problem solvers, Gerrig and Berndardo created a textual analog to circumstances of functional fixedness. In classic problem solving research, functional fixedness refers to situations in which problem solvers have experienced a standard use of an object and are, therefore, unable to conceptualize it in a novel way to facilitate a solution (Duncker, 1945; Maier, 1931). For the text-based experiment on functional fixedness, the narrative shifted from Bond's fountain pen to his comb. In the *used comb* version, the story began with a scene in which Bond used his comb for its ordinary function:

> Bond looked in the mirror of his hotel room to make certain that his black tie was centered in his collar. He noticed that his hair was just the least bit mussed, so he extracted his comb from his pocket and smoothed his wandering locks back into place.

In the *unused comb* version, the comb does not figure in the opening scene (instead, Bond plucks a white thread from his lapel to complete his grooming). Neither version of the story mentioned the comb again until (in both versions) Chiffre removed it: "Le Chiffre pulled out Bond's pocket comb and ran his finger down its teeth. He smiled broadly, and flipped the comb well out of Bond's reach."

In both versions of the text, Bond has lost his comb and, thus, has the same number of potential solutions for escape. However, Gerrig and Bernardo predicted that participants who read the *used comb* version of the story would experience less suspense because they were likely to conceptualize the comb as exactly that, a comb. As such, they should not experience the comb's removal as a foiled means of escape. Participants' ratings confirmed that prediction: People who read the *unused comb* version (M=3.96) provided reliably higher ratings than people who read the *used comb* version (M=3.41).

These results are consistent with the prediction that readers function as problem solvers in their experience of suspense. Because we would expect real-world side participants to behave in a similar fashion, this prediction flows from the participatory perspective. However, these experiments rely on readers' global reports of suspense. Although self-reports have been the norm for research on suspense, it would be useful to have moment-by-moment data to confirm that readers are participating—hoping to find Bond a solution—as the text unfolds.

6. Conclusion

In this chapter, we have provided a sketch of the participatory perspective on readers' narrative experience. This perspective is anchored in a more general account of language use that makes reference to the frequency with which people are cast in the role of side participant. The perspective focuses attention on processes that are commonplace in readers' experiences but have been overlooked by canonical theories of text processing.

We have reviewed empirical projects that illustrate several ways in which readers' processes and representations are affected by their participatory responses. The first pair of projects demonstrated the impact of readers' preferences on their experiences of narrative outcomes. Even when, for example, a time shift made a particular outcome improbable, readers found that outcome easier to assimilate when it was their preferred outcome. The next project focused on readers' responses to characters' decisions. The results suggested that readers participate in characters' decisions: When, for example, characters make decisions that readers find unpalatable, readers expect the characters to suffer negative consequences.

The final pair of projects examined readers' responses to mysteries. One project focused on circumstances in which texts introduce characters by proper names (e.g., Billy) but provide no other immediate information to resolve the character's role in the narrative world. The results indicated that characters who remain unresolved also retain relative prominence in discourse representations. A second project examined circumstances in which mysteries lead to feelings of suspense. The data suggested that readers function as problem solvers. Their experiences of suspense are heightened as paths to a solution fall away. Taken together, this series of projects illustrate the variety of ways in which participation structures readers' narrative experiences.

We opened this chapter by describing a critical episode from *Bridge of Sighs*—an episode that reverberates through the entire novel. From our perspective, the episode has narrative power exactly because readers are so highly motivated to function as side participants in the events. To the extent that readers expend mental effort to forestall whatever misfortune awaits Lou, readers have a stake both in that immediate misfortune and all its subsequent echoes. Readers' experience of this episode illustrates quite plainly why theories of text processing should embrace the concept of participation.

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CHAPTER EIGHT

Aging, Self-Regulation, and Learning from Text

Elizabeth A. L. Stine-Morrow *and* Lisa M. S. Miller

Contents

Abstract

There is general agreement that language comprehension depends on both automatic, modular, interpretive processes (often modeled as a spread of activation or a resonance-based activation), and more resource-consuming, integrative, post-interpretive processes that are used to resolve meaning. Considerable effort has been devoted to understanding how readers and listeners do resolve meaning, often under the assumption that there is a single veridical meaning to be represented. Recently, there has been a greater focus on how the self-regulation of attention may give rise to different representations. Because aging is often associated with change in competencies and motivation that can affect such regulation, adult development can provide an interesting window into these processes.

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1. Introduction

Language and text processing serves many functions throughout the lifespan. Language is a primary conduit of information acquisition, and contributes to cementing human relationships, regulating emotion, and building cognitive reserve (Bialystok, Craik, & Freedman, 2007; Smith, 1998; Stine-Morrow, Miller, & Hertzog, 2006). In this chapter, we explore language understanding as a self-regulated activity that shows change through adulthood in concert with developmental change in cognition and lifespan context.

Perhaps contrary to outward appearances, reading is a very active process (Just, Carpenter, & Miyake, 2003; Nell, 1988). Considerable attention has been devoted in the research literature to define categories of language processes that are automatic and obligatory (modular), as opposed to those that are resource consuming and optional (Caplan & Waters, 1999; Graesser, Singer, & Trabasso, 1994; McKoon & Ratcliff, 1992). Perhaps as a consequence of the fact that psycholinguistics has been dominated by the study of syntactic parsing and word-level processing, which do appear to be largely modular, much research has been devoted to understanding the nature of obligatory computations. Principles defining the nature of optional and integrative processes are perhaps less well understood. Clearly, both classes of processes are critical to language understanding and learning from text (Rapp & van den Broek, 2005), but there is little understanding of how these processes are regulated.

Aging brings an array of changes in cognitive resources, lifespan context, and motivations for engaging new experiences, so that the significance of viewing cognition as self-regulatory is heightened. To lay the groundwork for discussing language processing as a self-regulated activity that changes through the adult lifespan, we first consider (a) the underpinnings of language understanding and learning from text and (b) the nature of cognitive change with age.

2. What Does It Mean to "Learn from Text"?

2.1. Assumptions About Representation

Learning from text is typically conceptualized as the construction of a multifaceted mental representation as a consequence of engagement with text (Graesser, Millis, & Zwaan, 1997; Kintsch, 1998; Radvansky & Dijkstra, 2007; Stine-Morrow, Miller, et al., 2006; Zwaan & Rapp, 2006). Readers create a representation of the meanings of individual words, the ideas given directly by the text (called the "textbase"), the situation implied by the discourse (the "situation model"), and the structural form of the discourse (e.g., narrative form, argumentation form of expository text). At the word level, the lexicon is accessed to give rise to conceptual representations of words (often modeled as a collection of features). At the textbase level, relationships among concepts are identified to construct propositions (idea units) that are integrated to yield a semantic representation of the content given directly by the text.

At the discourse level, readers build a model of the situation suggested by the discourse, though the nature of this representation (and underlying processes) are subject to debate. In the Kintsch (1988, 1998) approach, the situation model is a proposition-based construction in which ideas from the textbase are integrated with ideas from the knowledge base. Interactions between text coherence and knowledge (e.g., the finding that high-knowledge readers show better memory for low-coherence texts while low-knowledge readers learn more from coherent texts) has been explained in terms of the rich situation model that high-knowledge readers generate through inference (McNamara, Kintsch, Songer, & Kintsch, 1996). The event-indexing model (Zwaan, Langston, & Graesser, 1995; Zwaan, Magliano, & Graesser, 1995), which was developed specifically to explain narrative understanding, assumes that the reader tracks a protagonist along five specific dimensions (space, time, goals, intentions, emotion). Evidence for this perspective includes the well-replicated finding that discontinuities in these dimensions (e.g., a shift in the narrative time line or setting) produce increments in reading time (Morrow, Bower, & Greenspan, 1989; Rinck & Bower, 2000; Stine-Morrow, Morrow, & Leno, 2002; Therriault, Rinck, & Zwaan, 2006). Finally, the situation model has been described as a representation that is grounded in experience so that reading stimulates a perceptual simulation of events described by the text (Barsalou, 1999, 2008; Glenberg & Robertson, 2000; Morrow, Greenspan, & Bower, 1987; Zwaan & Taylor, 2006). Assuming that the aspects of events tracked in the event-indexing model entail a simulation of narrative events, we might think of the event-indexing model as a specific instantiation of the broader principle of embodied cognition. So the two fundamental ways of thinking about the situation model are in terms of (a) an integrated network of propositions that fills in the gaps of and elaborates on a text, or (b) a mental simulation of events or processes suggested by the text.

Also at the discourse level, readers represent structural and rhetorical forms that, among other things, guide how propositional content is integrated and what sort of knowledge is to be brought to bear in interpretation. For example, narratives often consist of a series of episodes built around the goals of one or more protagonists (Mandler & Johnson, 1977). A variety of expository forms have been identified (e.g., compare–contrast, thesis–evidence), with some evidence that text memory can be enhanced when readers are explicitly instructed in analysis of the expository form (Britton, 1994; Meyer & Poon, 2001; Meyer, Young, & Bartlett, 1989). This list is not exhaustive. For example, cultural conventions on particular sorts of communicative forms can be quite narrow (e.g., recipes, assembly instructions, medication instructions).

Potentially, then, "learning from text" is a far-flung endeavor, which can encompass anything from the encoding of isolated facts to the reflective construction of how a physical or social system works to the vicarious experience of new emotional repertoires.

2.2. Assumptions About Process

One of the fundamental problems that theories of discourse understanding have to solve is how complex mental representations can be created from linear language input within a working memory system that is very limited (Daneman & Merikle, 1996; Miller, 1956; Unsworth & Engle, 2007). One theoretical solution to this problem is incrementality, the notion that language structure is computed one word at a time (Pickering & van Gompel, 2006), with responses to ambiguity providing a window into when readers are led astray. Another solution is the "input cycle," the psychological moments in which segments of text (e.g., clauses or short sentences) are in attentional focus (Kintsch, 1988, 1998). It is generally assumed that the language representation shows dynamic change as the reader moves through a text.

There are three interrelated issues that have driven much of the research in this area over the years. One question is whether the products of computations from different sources (word, textbase, discourse, knowledge) are available to one another during incremental construction of the representation (interactive), or whether computations at different levels are conducted independently of the output at other representational levels (encapsulation) (Fodor, 1983; Just & Carpenter, 1987). Another question is the extent to which the array of language processes draws on general working memory resources as opposed to a specialized language resource that is unaffected by other cognitive demands (Caplan & Waters, 1999; Just & Carpenter, 1992). A third issue is the extent to which reading relies primarily on memory-based (bottom-up; resonance) versus explanation-based (top-down) processes (Albrecht & Myers, 1995; Graesser et al., 1994). The construction–integration model (Kintsch, 1988), for example, explicitly incorporates both types of processes. This model assumes that readers use construction processes that activate representations in a largely unconstrained fashion. These processes are then modulated by top-down integrative processes that constrain the multiple options that were generated in a bottom-up fashion.

This chapter is not really about any of these issues. Rather, we take for granted that certain language processes under certain conditions can be encapsulated or interactive; resource-constrained or automatic; and resonance-based or strategic. The particular issue we wish to explore is the extent to which readers regulate these computations as a function of individual differences in processing capacity and knowledge. Thus, we assume that language computations generally require some ''mental workload'' (Just et al., 2003), measurable in terms of both behavior (e.g., processing time, patterns of memory performance) and neural process (e.g., fMRI, ERP); in fact, behavioral and neural assessments of mental workload can produce homologous results (Mo, Liu, Jin, Ng, & Lin, 2006). Rather than asking questions about whether readers conduct processes *x* and *y*, our questions are more of the sort: is there variability in the extent to processes *x* and *y* are conducted? how does the thoroughness with which processes *x* and *y* are conducted relate to the products (e.g., comprehension, memory)? what are the principles governing the completeness of computations *x* and *y*? how do age-related changes in cognition and motivation impact the extent to which computations *x* and *y* are conducted, and the relationship between the completeness of computations and the quality of what is produced? In the remainder of this section, we consider evidence for the basic architecture of the system we have been describing.

2.3. Evidence for Distinct Levels of Linguistic Analysis and Text Representations

There is considerable evidence that processes used to construct word, textbase, and situational representations derive from distinct psychological systems. Processing time is one sort of evidence. Longer words and/or words that are less frequent in the language take longer to verify in lexical decision or naming tasks, and also take less time to process in reading (e.g., Aaronson & Scarborough, 1976; Just & Carpenter, 1980; Spieler & Balota, 2000). Controlling for features of the surface form, reading time for sentences increases with textbase complexity (e.g., the number of propositions and new concepts; Kintsch & Keenan, 1973; Kintsch, Kozminsky, Streby, McKoon, & Keenan, 1975). Controlling for features of the surface form and the textbase, processing time increases as a function of various demands to construct a situational representation. For example, reading time in narratives increases for text segments in which there is a situational discontinuity as when new characters are introduced or when a character moves to a new location or when there is a jump in the narrative time line (e.g., Morrow et al., 1987; Rinck & Bower, 2000), and reading time accelerates with depth into narrative episodes (e.g., Haberlandt, 1984; Stine-Morrow, Miller, & Leno, 2001). The constellation of these demands can be measured as an array of coefficients, in which reading time is regressed onto a set of features representing these demands (e.g., word length to represent orthographic decoding, number of propositions in sentence reading time or the introduction of a new concept in word reading time, and so forth) so that reading times for individual readers can be decomposed into resources allocated to these processes. Coefficients reflecting word and textbase processing show some intraindividual consistency over a 1-month interval (i.e., moderate test–retest reliability; Stine-Morrow et al., 2001). These coefficients also show consistency as readers move from one genre of text to another (Stine-Morrow, Miller, Gagne, & Hertzog, 2008). Collectively, such data suggest that the allocation policies with which readers approach text may be thought of as "habits of mind" that are relatively enduring patterns of engagement. Importantly, when these individual coefficients are submitted to factor analysis, the factor structure maps onto distinctions among word, textbase, and discourse that we have been discussing (Stine-Morrow et al., 2008).

Evidence for this distinction among different levels of text representation and process can be found in recognition memory as well. In a clever paradigm developed by Schmalhofer and colleagues (Kintsch, Welsch, Schmalhofer, & Zimny, 1990; Schmalhofer & Glavanov, 1986), different levels of representation are operationalized as the reader's ability to discriminate among different sorts of statements strategically designed to draw on particular representational forms. Consider the following example. Suppose the target text was about dinner at a Japanese restaurant and there was a sentence in the text, *After consulting the waiter, Lorraine ordered the tuna maki.* A reader who can correctly recognize the verbatim statement from the text but correctly reject a paraphrase (e.g., *Lorraine ordered the tuna maki after consulting the waiter*) must have retained a representation of the surface form in memory. Analogously, a reader who asserts that an accurate paraphrase was read but rejects a statement that includes ideas not included in the original text (e.g., *Lorraine ordered the eel maki after consulting the waiter*) has presumably lost the surface from, but retained a representation of the propositional content of the textbase. Finally, a reader who accepts a statement expressing ideas not in the text but consistent with the larger situation (e.g., the eel example) but rejects a statement not consistent with the larger situation (e.g., Lorraine ordered spaghetti) has demonstrated that he/she understands the situation even if the particulars of the narrative were not retained. Using a signal detection approach, discriminability (d') between these classes of statements is calculated to measure sensitivity to surface, textbase, and situational representations. Such an approach has been used to dissociate among these different representational forms, for example, showing differential decay rates (the surface form decays relatively quickly; the situational representation, slowly) (Kintsch et al., 1990). Similarly, assuming that familiarity judgments reflect access to the textbase representation and recollection reflects access to the situation model, Long, Wilson, Hurley, and Prat (2006) have used a remember–know paradigm to dissociate these levels of representation.

Finally, there is a rich literature emerging that explores the neural substrates of these different levels of process. One technique used is to contrast patterns of activation in fMRI while individuals read text in one of three permutations that presumably involve varying degrees of word, textbase, and situational processing: (a) intact narratives (requiring all three forms of processing); (b) individual sentences randomized from comparable narratives, so that sentence processing is required without narrative context while controlling for surface form and propositional content, and (c) individual words randomized from the narratives, so that the same words are processed but there is neither sentence nor narrative coherence. Using this approach, Xu, Kemeny, Park, Frattali, and Braun (2005) found distinct patterns of activation across conditions. At the risk of oversimplifying, relative to a letter string control, reading words engenders activation primarily in left perisylvian areas, including the middle and inferior temporal gyri, and in premotor areas; relative to the word condition, reading sentences produced different patterns of activation, including more anterior activation of the left temporal lobe and pronounced activation of the frontal operculum (associated with syntactic processes); and relative to the sentence condition, discourse comprehension produced activation in the right hemisphere and there was more frontal involvement. Similarly, Yarkoni, Speer, and Zacks (2008) used fMRI to compare the brain's response to coherent narratives and to narratives in which individual sentences were randomly arranged. They found that coherent narratives (but not individual sentences) produced activation in the dorsomedial prefrontal cortex. They also examined change as function of the time course in narrative processing to show distinct processing signatures for situation construction (posterior parietal activation) and situation maintenance (frontal and temporal activation).

A distinction among word, textbase, and situational representations at the neural level has also been demonstrated with event-related potentials (ERPs), a measure of the electrophysiological response of the brain that is very time sentence when averaged over multiple trials. Yang, Perfetti, and Schmalhofer (2007) had participants read two-sentence passages in which a target word in the second sentence was either explicitly mentioned in the first sentence (same word), a paraphrase of a concept mentioned in the first sentence (new word, same textbase), an implication (inference) from the first sentence (new word and textbase, same situation), or not referenced in the first sentence (new word, textbase, and situation). These different demands for integration were reflected in distinct patterns, suggesting distinct neural responses when novel lexical, conceptual, and situational information is encountered in processing language.

Neural response may be further differentiated depending on the situational features processed. For example, Ferstl, Rinck, and van Crammon (2005) found that while temporal inconsistencies in narratives evoked greater activation in the lateral areas of the prefrontal cortex, emotional inconsistency evoked activation in the ventromedial prefrontal cortex as well as in the amgdala complex. These data provide support for the notion that reading creates an embodied understanding of the narrative situation.

To recap, both behavioral and imaging data provide support for a conceptualization of language processing as a richly complex activity that can be parsed into sets of processes that compute word meanings, construct the ideas contained in sentences, and create an embodied representation of the situation suggested by the discourse. One implication of an embodied situation is that the neural representation must be distributed. Thus, it is certainly a gloss to group situation model processes under a single umbrella.

3. The Nature of Cognitive Aging

3.1. Multiple Trajectories of Cognitive Change

Cognition in adulthood is often characterized in terms of dynamic change in two competing forces. "Mental mechanics"—the ability to quickly transform information and effectively control attention to respond to changing task demands, or the "basic architecture of information processing and problem solving" (Baltes, 1987, p. 614)—shows a monotonic decline through adulthood, as a consequence of a genetically driven senescence process. "Crystallized pragmatics" that draw on experience—the "context- and knowledge-related application of the mechanics of intelligence of processing" (Baltes, 1987, p. 614), such as vocabulary and domain knowledge—increase as a consequence of experience (Baltes, 1997). Age-related declines in mental mechanics have been conceptualized alternately as a decrease in working memory capacity (Bopp & Verhaeghen, 2005), a reduction in the speed at which elementary operations can be conducted (Salthouse, 1996), an inhibitory deficit in which working memory function is compromised by being cluttered with information that irrelevant or no longer relevant to the task or situation (Zacks, Hasher, & Li, 2000), and as declines in executive function that regulates cognition in part by maintaining the activation of goals to guide processing and limit the influence of irrelevant information (Braver & West, 2008).

There have been some excellent reviews of aging and language processing in recent years (Burke & Shafto, 2008; Meyer & Pollard, 2006; Radvansky & Dijkstra, 2007; Thornton & Light, 2006), so there is no need for a comprehensive review here. Rather, we focus specifically on the implications of divergent trajectories of mental mechanics and knowledge-based processes for constructing the language representation at different levels.

3.1.1. Consequences of Age Differences in Mental Mechanics for Text Processing

A consequence of age declines in mental mechanics is that age effects would be expected to be exacerbated for language processes and tasks that are relatively resource-demanding. There is considerable evidence to suggest that textbase processing heavily depends on mental mechanics. For example, Jefferies, Lambon Ralph, and Baddeley (2004) contrasted dual-task performance for unrelated and related sentences, and showed a larger dual-task decrement for unrelated sentences, "indicating a special role for attention in the binding of arbitrary combinations" (p. 638). Assuming that we can think of propositional coding as the binding of concepts that occurs as a result of instructions from the parser to make thematic role assignments (Kintsch, 1992, 1998), this aspect of language processing would be expected to be most vulnerable to age deficits (Old & Naveh-Benjamin, 2008).

While age deficits in memory for text are not as universal as they are in memory for other sorts of materials (e.g., word pairs or lists, actions) (Hultsch & Dixon, 1984), a comprehensive meta-analysis by Johnson (2003) suggested that age differences in memory for content are reliable (see also Zelinski & Gilewski, 1988). In fact, effective coding of propositional content takes more time for older readers than for young (Hartley, Stojack, Mushaney, Annon, & Lee, 1994; Stine & Hindman, 1994), and age deficits in sentence memory can be accounted for in part by this inefficiency in combination with a reluctance to allocate time to keep pace with this inefficiency (Hartley et al., 1994). Age deficits in text memory are also exaggerated by complex syntax, such as left-branching constructions, with differences largely explicable in terms of age differences in working memory (Kemper, 1987; Norman, Kemper, & Kynette, 1992). Because such complex syntactic forms require retention of a relatively larger number of concepts over a greater distance before semantic relationships can be resolved, binding deficits (Old & Naveh-Benjamin, 2008) would be expected to make it harder to complete propositional coding.

Age differences in mental mechanics have been argued to produce less of an effect on situation model processing relative to textbase processing (Radvansky, 1999; Radvansky & Copeland, 2004; Stine, Soederberg, & Morrow, 1996). For example, Radvansky, Zwaan, Curiel, and Copeland (2001) used the Schmalhofer recognition paradigm described earlier to show age deficits in memory for the textbase, but not for the situation model. Also, older readers slow down when encountering situational discontinuities as they read (Morrow, Leirer, Altieri, & Fitzsimmons, 1994; Morrow, Stine-Morrow, Leirer, Andrassy, & Kahn, 1997; Stine-Morrow et al., 2002). Older readers also show a perceptual symbols effect (i.e., faster verification for an object if its shape matches what is implied by a priming sentence, e.g., an eagle with open wings, after reading *The eagle was flying in the sky*, relative to *The eagle was perched in the tree*) that is at least as large as that found among younger adults (Dijkstra, Yaxley, Madden, & Zwaan, 2004).

However, there appear to be limits on this principle of situation model resilience, as when the construction of the situation model depends on retention of the textbase (Radvansky & Dijkstra, 2007). Copeland and Radvansky (2007) used a paradigm developed by Mani and Johnson-Laird (1982) to illustrate this point. They presented participants with descriptions such as, *The rose is above the lily. The tulip is above the orchid. The lily is to the left of the orchid.* Participants then had to select the correct arrangement of items (in this case, flowers) as an indicator that they had comprehended the spatial situation implied by the text. In this example, the concepts were described in an AB–CD–BD arrangement so that rose and the lily (AB) had to be held in mind and the tulip and orchid (CD) had to be held in mind before their relative spatial relationship could be disambiguated by the final statement describing the arrangement of the lily and orchid (BD). In this task, older adults had much more difficulty than the younger adults conceiving the situation suggested by the text. Importantly, older adults were at no special disadvantage when statements were presented in a way that enabled continuity in situation construction (e.g., an AB–BC–DC arrangement in which each statement creates incremental change in the situation). The fact that older adults did relatively well in the continuous condition suggests that they did not have difficulty in representing the spatial situation per se—and as such, jibes with the finding that older readers appear to be quite good at tracking a character through space in reading narratives (Morrow et al., 1994; Stine-Morrow et al., 2002). This is an interesting finding that hints that there may be boundary conditions on the principle of situation model resilience, e.g., when the textbase must be retained in working memory over some distance in the text before the situation is resolved.

3.1.2. Consequences of Age-Related Growth in Knowledge Systems for Text Processing

In a classic study, Hultsch and Dixon (1983) examined the effects of domain familiarity on text processing. They had older, middle-aged, and younger adults read biographical sketches about famous entertainers who were either well known within their generation, not well known to individuals within their age group, or well known across generations. Younger adults outperformed the older groups in the number of propositions recalled for the across-age story and the "young" story. However, the older adults recalled more from the "old" story than the other two groups indicating that pre-experimental knowledge is an important factor in immediate text recall. This study provided important early evidence that declines in mental mechanics could be offset by knowledge in text memory.

Subsequent research has sometimes found that age differences are reduced or absent among high-knowledge adults. One notable example is reported in a study examining age differences in the effects of aviation expertise. Morrow et al. (1994) had younger and older experts (pilots) and novices (nonpilots) read back air traffic control commands as typically required when communicating with air traffic controllers. They found that expertise mitigated age-related performance decrements such that age differences were reduced among experts relative to novices. However, comparable age declines in memory for text as a function of schema availability (Arbuckle et al., 1990; Miller & Stine-Morrow, 1998) and domain knowledge (Miller, 2003) have also been reported.

Other research has shown evidence that older adults are to some extent protected from declines by knowledge. Salthouse (2003) refers to this pattern as migration because in this case, the normative pattern is for aging individuals to "migrate" into the high-knowledge group (e.g., as with the typical increase in vocabulary knowledge with age). Rather than differential patterns of development among high- and low-knowledge individuals, migration implies that there are comparable age-related trajectories in performance as a function of knowledge, but that the increase in knowledge offsets declines in mental mechanics. So for example, when a task (e.g., text memory) depends on both fluid and crystallized abilities, the observed age trajectory might be flat or somewhat negative showing relatively gentle age declines. However, when the effects of knowledge are statistically controlled, the correlation between age and performance can become more negative. Such migration effects have been demonstrated for verbal ability (Stine-Morrow, Loveless, & Soederberg, 1996) as well as domain knowledge (e.g., Meinz, 2000; Miller, 2009b; Morrow, Menard, Stine-Morrow, Teller, & Bryant, 2001).

The effects of crystallized knowledge are also evident in brain function. Older adults with relatively high verbal fluency and vocabulary knowledge have shown exaggerated responsiveness in the N400 ERP component in spoken sentences (Federmeier, McLennan, De Ochoa, & Kutas, 2002). These data suggest that the typical growth in verbal ability with age may enable older adults to develop more distinctive text representations, making them more adept at detecting anomaly.

While it is clear that knowledge has beneficial effects on text memory (e.g., Cheisi, Spilich, & Voss, 1979; Spilich, Vesonder, Chiesi, & Voss, 1979), the underlying mechanisms of how knowledge affects language processing are not well understood. In fact, knowledge appears to have a paradoxical effect on language processing. On the one hand, knowledge schemas can facilitate the processing of unfamiliar words and the integration of concepts in discourse, so that reading can require less effort for one who is knowledgeable (Miller & Stine-Morrow, 1998; Sharkey & Sharkey, 1987; Wiley & Rayner, 2000). On the other hand, knowledge can consume processing capacity (Britton & Tesser, 1982) and evoke inference (McNamara et al., 1996; Miller, Stine-Morrow, Kirkorian, & Conroy, 2004; Noordman & Vonk, 1992; Noordman, Vonk, & Kempff, 1992), so that an expert reading in his or her domain of expertise may allocate more effort than a novice.

In the latter case, certain computations may take more time for readers who have relevant prior knowledge because this knowledge often requires "unpacking" for it to be applied to the text (Miller & Gagne, 2008), so that extra effort is productive. If we conceptualize knowledge as an integrated semantic network with varying levels of abstraction (Chi, Feltovich, & Glaser, 1981; Hayes-Roth, 1977; Thorndyke & Hayes-Roth, 1979), unpacking a text refers to processes associated with identifying and instantiating the lower-level particulars of this network (Britton & Tesser, 1982; Miller, 2003), as well as organizational and item-specific processing that enhance the distinctiveness of the text representation (Rawson & Van Overschelde, 2008). Readers do not typically access or fully instantiate all the particulars of constructs that could come to mind when reading a text but rather select ones that fit the context of the situation. Readers with more knowledge have more choices to make in selecting the appropriate meaning for the current purpose. While texts that draw exclusively on schematic knowledge offer few options for interpretation and so facilitate access to concepts and integration of these concepts (Sharkey & Sharkey, 1987), complex knowledge structures (such as may be the case in domain knowledge) require the reader to select among various substructures to determine what is relevant and important and consider how particulars of the text mesh with particulars of their knowledge base. Thus, as we consider later, knowledge can impact the regulation of attention during reading so as to stimulate processing in a way that is productive.

3.2. The Motivational Context of Cognitive Aging

3.2.1. Social–Emotional Context

A central theme to emerge in the literature on adult development and aging over the last decade or two is that of selectivity (Baltes, 1997; Baltes & Baltes, 1990; Carstensen, Mikels, & Mather, 2006). A decline in resources along a variety of dimensions entails that later adulthood be defined by the selection among an array of options available. One important principle of selectivity that has garnered some support is that the more limited time horizon that comes with aging engenders a heightened concern with satisfaction of social and emotional goals relative to cognitive and information-acquisition goals (Carstensen, 1995). Because discourse processing contributes to both sorts of functions, it is worth considering evidence concerning age-related change in the processing of emotion.

Research suggests that there is preservation in processing emotionally valenced material in later life relative to neutral material (e.g., Denburg, Buchanan, Tranel, & Adolphs, 2003). Other work suggests that there is greater preservation of processing positive relative to negative emotion (e.g., Charles, Mather, & Carstensen, 2003; Leigland, Schulz, & Janowsky, 2004; see Mather & Carstensen, 2005 for a review). For example, in an examination of memory for words and faces, Leigland et al. (2004) found that older adults showed a slightly larger memory advantage after a 30-min delay for positive stimuli (relative to negative and neutral) than did younger adults.

In a recent study examining the neural processes that underlie emotional memories, Kensinger and Schacter (2008) found that older adults showed greater activity in the left prefrontal and temporal areas (where positive information is processed) as well as in the medial prefrontal cortex and cingulate gyrus. Because these areas are also associated with self-referential processing, which may lead to greater memory performance, the authors suggest that self-referential processing may underlie the positivity effect. Knight, Seymour, Gaunt, Nesmith, and Mather (2007) monitored eye movements of younger and older adults while they were viewing pairs of negative, positive, and neutral faces and pictures. Images were viewed under full and divided attention conditions. They found that when older adults devoted full attention to pairs of images, they avoided allocating attention to negative information. However, under divided attention conditions, they viewed negative information more than other types of information. Together, these findings suggest that the positivity bias among older adults may be attributable to greater self-referential processing that is more likely when older adults have attentional resources necessary to exercise this type of self-regulatory control. The implication of this work to language comprehension is that older readers may actively attend to aspects of text that have self-relevance or that contain emotional information. Few studies have directly investigated this notion; however, Carstensen and Turk-Charles (1994) found age-related declines in memory for neutral content of texts but not for emotional content. Adams, Smith, Pasupathi, and Vitolo (2002) reported that age deficits in story recall were eliminated when the goal for retrieval was to tell a story to a child, rather than to recall the story to an experimenter. It could be that the socioemotional context of storytelling impacts goal-directed reading by evoking processing relative to the self as a storyteller (e.g., in the role as a grandparent or parent).

3.2.2. Self-Perceptions

As the above research indicates, aging appears to bring an orientation toward emotion regulation and sensitivity to social context, which influences how older adults attend to, process, and remember information (see also Hess, 2005 for a broader review). Another set of factors that may influence how an older adults processes information surrounds the self-perception of his or her abilities. Self-perceptions such as self-efficacy and control beliefs regarding one's skills and abilities as well as the likelihood of comprehension success may influence the manner in which attention is allocated and the degree to which learning and memory result (Bandura, 1997).

The evidence is ambiguous as to whether there are age differences in mean levels of self-efficacy and control beliefs related to cognitive functioning (e.g., Miller & Lachman, 1999), possibly because beliefs are highly context-specific and assessments are sometimes relatively general in nature (Lachman, 1986). However, cognitive control beliefs that are specifically related to memory functioning are more likely to show age-related declines (e.g., Andreoletti & Lachman, 2004; Berry & West, 1993). Even when there is age constancy in mean levels of cognitive control beliefs, the effects of beliefs on performance can depend on age for a variety of reasons. In general, the argument is that effort and strategies may be particularly important for individuals when they are performing a challenging task (e.g., Bandura, 1997). For example, older adults who feel they have little control over their memory abilities are less likely to persist when performing a challenging task and are less likely to identify strategies that will allow them to remember (Lachman, 2006; Miller & Lachman, 1999; Welch & West, 1995), and this lack of persistence can have especially negative effects for older adults (e.g., Stine-Morrow, Shake, Miles, & Noh, 2006).

4. Self-Regulated Language Processing

To this point, we have described a system of language understanding in which readers create a multileveled representation (word, textbase, situation model, discourse structures) and a view of adult development in which change is multifaceted (e.g., declines in mental mechanics, growth in knowledge, increased focus on social–emotional concerns, changes in self-perceptions). In this section, we explore ways in which language processing can be self-regulated and consider how this informs the study of the adult development of language understanding and learning from text.

4.1. Basic Rationale for Considering Language Processing as Self-Regulatory

4.1.1. Self-Regulatory Processes in Learning

In recent years, self-regulatory processes of learning have been of increasing interest, providing a complementary perspective to a prevailing systems approach in memory and cognition (Benjamin, 2008; Gopher & Koriat, 1999). There are two contrasting views of how learners regulate processing that have driven much of the research in this area. One is that learners use a heuristic in which they seek to reduce the discrepancy between where they are in the learning process and where they would like to be. This notion of discrepancy reduction (DR) has been examined in part through the use of a judgment-of-learning paradigm in which individuals study information and then provide judgments or estimates regarding the probability that they will be able to remember the information. In general, findings suggest that younger and older adults allocate more study time to items they perceive to have learned less well, consistent with the basic premise of discrepancy reduction (Dunlosky & Connor, 1997; Dunlosky & Hertzog, 1997; Nelson, Dunlosky, Graf, & Narens, 1994; Thiede & Dunlosky, 1999). However, when criteria for learning are made relatively lenient or when time for learning is constrained, there can be a shift toward easier materials (STEM; Dunlosky & Thiede, 2004; Thiede & Dunlosky, 1999). A contrasting model that accommodates the STEM effect is the "region of proximal learning" (RPL) idea that learners allocate effort so as to encode information just within their grasp. So rather than focusing on the information that is the most difficult (i.e., furthest away from the state of being learned), learners focus on items of intermediate difficulty. There has been some evidence garnered for this view as well (Kornell & Metcalfe, 2006; Metcalfe, 2002; Metcalfe & Kornell, 2003, 2005). For example, Metcalfe and Kornell (2005) have argued that items that have already been learned are much less likely to be revisited and that it is the difference in time allocation to learned and unlearned items that accounts for discrepancy reduction; they presented evidence that when learned items are removed from the pool, relatively easier items receive more attention. Thus, whether learners normatively adopt a DR or RPL heuristic may depend on contextual factors (e.g., criteria for success, time constraints, stage of learning). This does not speak to what heuristic is optimal for learning, however. There is some evidence that the extensiveness of DR is predictive of final performance (i.e., those who study the most difficult items do better overall) (Thiede, 1999; Thiede, Anderson, & Therriault, 2003), but whether the DR or RPL heuristic is optimal for learning may depend on the shape of the uptake function (i.e., rate of learning relative to effort allocated) and/or stage of learning (Son & Sethi, 2006).

Applying this theoretical framework to understanding how people regulate text understanding is a nontrivial problem. One reason is that this monitor-and-control framework assumes selection and processing of discrete items (in discrete bouts of learning), which is easy to apply to learning structurally simple materials (e.g., foreign language vocabulary, short sentences) and valuably so, but less obvious in the case of extended passages of discourse, in which attention can be allocated simultaneously or selectively to different levels of representation as one proceeds through a text. To take the simple case, however, one might simply ask whether DR or RPL theory can predict the selection and allocation of time to short texts. For short texts (e.g., sentences and haikus), evidence for discrepancy reduction has been found (Miles & Stine-Morrow, 2004; Son & Metcalfe, 2000), but for longer texts that are demanding in their integration requirements (e.g., biographies of several pages, sonnets read under time pressure), the evidence is more mixed (Son & Metcalfe, 2000; Thiede et al., 2003).

A number of studies have suggested that the goals with which readers approach text affect how they read and what they take away from the text. For example, individuals who read with a goal to remember allocate attention more to textbase features than those who read for entertainment (Zwaan, Magliano, et al., 1995). A memory reading goal is more likely to yield a robust textbase representation whereas a comprehension reading goal is more likely to focus on a situation model representation.

van den Broek, Lorch, Linderholm, and Gustafson (2001) suggest that goals affect readers' standards of coherence, and these standards in turn influence the extent to which various types of inferences are generating while reading. To examine this issue, van den Broek et al. (2001) asked individuals to read for entertainment or to learn from the text. To examine the types of inferences individuals generated, they were asked to think-aloud while reading and were later asked to recall the text. Results showed that individuals who read for entertainment generated self-referent statements and showed relatively poorer memory for the text. On the other hand, those who read to learn generated backward and forward inferences that created greater coherence and showed greater memory performance. The authors suggest that the reader goals affect the standard of coherence that is expected while reading, and this turn affects the quality of the representation.

Similarly, expectations for genre can influence the representation that is constructed. Zwaan (1994) presented the same text as either a newspaper article or a literary story and found that readers approached the text differently depending on which genre they thought they were reading. When individuals read with a literary perspective, they read more slowly and showed better memory for the surface form of the text. In contrast, those who read with a newspaper perspective showed better memory for situational information. Data such as these suggest that the standard of coherence may not be a unitary construct when it comes to learning from text. Rather, the framing of learning heuristics in terms of discrete bouts of learning may have to give way to a view in terms of heuristics that guide selective develop of different facets of an integrated representation.

4.1.2. Underspecification and "Good-Enough" Processing

Perhaps as a swing of the pendulum away from the emphasis on automaticity and obligatory demands of language processing, a number of papers over the last few years have considered individual variability in the thoroughness with which linguistic computations are conducted (Christianson, Hollingsworth, Halliwell, & Ferreira, 2001; Sanford & Graesser, 2006; Sanford & Sturt, 2002; Stine-Morrow, Miller, et al., 2006). The take-home message here is that sometimes (and perhaps even often) readers create underspecified representations of the language input that are "good enough" for the current purposes of reading. In some ways, this reflects the larger zeitgeist of cognitive science that acknowledges the here-and-there quality of attentional control (Kane, Brown, McVay, Silvia, Myin-Germeys, et al., 2007; Raichle, MacLeod, Snyder, Powers, Gusnard, et al., 2001).

Note that there are actually two parts to this argument. The first is simply that the representation created from language is invariably and inevitably incomplete. This is obvious to anyone who has ever graded student papers or tried to recount a movie plot in some detail to a friend. There is increasing evidence that readers "zone out" and do not always conduct full analysis of language input (Hannon & Daneman, 2004; Smallwood, Schooler, & McSpadden, 2008). Even syntactic analysis, the prototypical example of the modular and encapsulated language process appears to be subject to underspecification. Recent research on comprehension in the face of syntactic ambiguity illustrates this point nicely. For example, Christianson et al. (2001) found that in encountering sentences like, *When Anna dressed the baby spit up*, readers are likely to affirm that Anna dressed the baby *and* that the baby spit up. Thus, along the garden path, readers activate both meanings (baby as the object of being dressed, and as the agent of spitting up), and even though the final correct parse forbids one interpretation, output from the illicit parse appears nevertheless to linger, resulting in less than full understanding of the ideas expressed by the sentence (e.g., missing that Anna actually dressed herself and inappropriately retaining the idea that she dressed the baby).

The second part to the argument is that people vary in the specificity (or fidelity) with which they create representations from language and that this has implications for language performance. In fact, there is considerable interindividual variability in how attention is allocated to language computations, which is correlated with language performance (Stine, 1990; Stine-Morrow et al., 2002; Stine-Morrow, Gagne, Morrow, & DeWall, 2004; Stine-Morrow et al., 2008). Recent findings in neuroscience also support this view with patterns of neural activation during reading predicting subsequent comprehension and memory performance (Hasson, Nusbaum, & Small, 2007; Yarkoni et al., 2008).

4.1.3. Age Differences in Underspecification?

Little research has explicitly examined the hypothesis that underspecification is exaggerated with aging, though some of the research reviewed earlier (e.g., age differences in recall for propositional content of text) might easily be viewed in that light. Interestingly, in spite of early evidence that age differences in the distinctiveness of encoding played a role in memory deficits generally (e.g., Craik & Jennings, 1992; Rabinowitz & Ackerman, 1982), the hypothesis of semantic deficits underpinning age differences in memory was rejected early on (Light, 1991). This was a reasonable conclusion based on the available evidence at the time for age constancy in word associations (Burke & Peters, 1986), semantic priming (Burke, White, & Diaz, 1987), instantiation of word meanings in context (Light, Valencia-Laver, & Zavis, 1991), and speed to verify bridging inferences (Zelinski, 1988). However, a (slightly nuanced) version of this idea may be worth reconsidering in light of more recent data.

The N400 component of ERPs (e.g., *Freddie's mother told him to take his elbows off the...tiger*, as opposed to the more expected ending...*table*) is somewhat reduced in amplitude and peaks later among older adults relative to younger adults (Federmeier & Kutas, 2005). Also, older brains react to an unexpected word that is from the same semantic category as the expected word (e.g., in this case, *chair*) to the same extent as they do to anomaly, while younger adults' brain response is more graded (i.e., as though *chair* is a somewhat anomalous, but not completely) (Federmeier et al., 2002). Federmeier and colleagues have interpreted such findings as showing that younger adults create a relatively well-specified representation of the text and use linguistic context to actively predict what is to come (*chair* then is somewhat less surprising because it comes from the same semantic category as the expected *table*). Older adults, by contrast, do not construct specific predictive representations, but attempt to integrate the meaning as the sentence unfolds. Note that older adults certainly do show a brain response to anomaly (especially those with high verbal ability; Federmeier et al., 2002), but such data suggest that the construction of the semantic representation of the sentence may develop somewhat more slowly among older adults and/or be less distinctive in its construction (with less specified development of semantic features).

In the arena of syntactic underspecification, older adults show evidence of being more likely than the young to retain the propositional content from the illicit parse (Christianson, Williams, Zacks, & Ferreira, 2006). So in the Anna (not) dressing the baby example, older adults are similar to the young in correctly endorsing the interpretation that the baby spit up, but they are more likely than the young to endorse the syntactically illicit interpretation that Anna dressed the baby (for a similar effect at the situation level, see Hamm & Hasher, 1992). Christianson et al. interpret these findings as evidence for an increased reliance with age on a "good-enough" processing heuristic driven by a working memory declines that make it more difficult to recover the surface form that would allow a syntactic reanalysis. Older adults also show evidence of underspecification in thematic role assignment in sentence understanding (i.e., who did what to whom?). Contrary to what is one might expect, older adults show less of an increase in reading time for object-relative constructions (e.g., *The governor who implicated the architect in the scheme accepted the bribe*) than for subject-relative constructions (e.g., *The governor who the architect implicated in the scheme accepted the bribe*) relative to younger adults, suggesting that older adults do not fully analyze the more difficult object-relative clause (Stine-Morrow, Ryan, & Leonard, 2000).

When directly probed, both younger and older adult had more difficulty correctly identifying thematic roles (e.g., *who implicated someone in the scheme?*).

Evidence from resource allocation in reading also suggests that the textbase representation may be less well specified during reading. Age deficits in text memory are often preceded by age differences in attentional allocation to instantiating and integrating new concepts during reading (Radvansky et al., 2001; Stine, 1990; Stine-Morrow, Shake, et al., 2006), suggesting that older adults may be less likely to encode the specific ideas from text as thoroughly as the young. Eye movement research reveals that older readers may be more likely to skip words as they read, a tendency that Rayner, Reichle, Stroud, Williams, and Pollatsek (2006) have referred to as "risky" reading.

Not all research is consistent with this view. Daneman, Hannon, and Burton (2006) asked younger and older adults to read a series of short passages, some of which contained an anomalous phrase, and then answered a question. For example, in a story about Amanda staying up all night drinking coffee to study, she is bouncing off the walls because she had taken too many tranquilizing stimulants, and participants were asked what Amanda should do. College-aged readers are notoriously bad at noticing such anomalies (Barton & Sanford, 1993). Daneman et al. showed that older adults are as good as (or as bad as) younger adults in detecting such anomalies, but no worse. In fact, in tracking the eye movements of participants, these researchers showed that older adults who detected these anomalies spent longer on the anomalous phrase (i.e., tranquilizing stimulants). When the anomalous phrase was internally coherent (but still inconsistent with the passage; e.g., tranquilizing sedatives), older readers were actually likely to notice the anomaly sooner than the young (on first-pass fixations, rather than in looking back to reread).

In another investigation of age differences in underspecification, Price and Sanford (2008) presented sentences like, *Simon sat down on the chair near the beach hut*, and then presented them again in the same form or with a slight change (e.g., Simon sat on a seat or rock instead), asking participants to indicate whether the sentence was changed. Older adults were no less likely to notice the change (after a short delay) relative to the young, suggesting that they did not necessarily encode the idea of the sentence in a more shallow way. Interestingly, when the focus of the sentence was altered with a cleft construction (e.g., *What Simon sat on was the rock* vs *It was Simon who sat on the rock*), older listeners were relatively more affected by the focus condition (i.e., especially good at recognizing the change when the syntactic construction put the critical concept in focus and especially bad at recognizing the change when the syntactic construction put the focus on another concept). This is interesting because it suggests that older adults may be particularly adept at using cues to direct attention to concepts and ideas that are more important. Thus, older adults may not simply encode textbase ideas less thoroughly (Radvansky et al., 2001; Stine-Morrow et al., 2004), but rather be more selective in which ones receive attention.

4.2. The Self-Regulated Language Processing Model

The self-regulated language processing (SRLP) model was proposed as an organizing framework for understanding attentional engagement during reading and how such engagement impacts learning (Stine-Morrow, 2007; Stine-Morrow, Shake, et al., 2006). As such, the intent was to provide a rapprochement between theories of language processing and metacognitive theories of learning (see Figure 1). The key idea is that the construction of the different levels of the text representation (word, textbase, situational/discourse) are independently regulated such that the

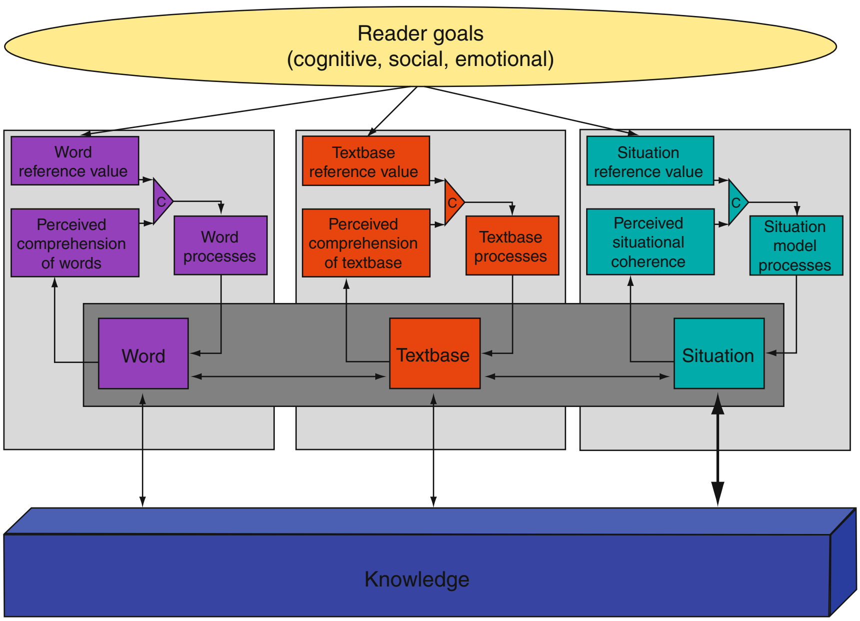

Figure 1 The self-regulated language processing (SRLP) model (Stine-Morrow, Miller, et al., 2006). Discourse comprehension and memory are assumed to depend on the construction of multiple levels of representation that are interactive and yet independently regulated. Reference values (or standards of comprehension/coherence) at each level—against which perceived representational fidelity is compared—is determined in part by the goals of the reader. Consequently, representations of the surface form (words), the proposition-based ideas given directly by the text (textbase), and the situation implied by the text (situation model) are constructed to varying levels of fidelity that depend on the goals and knowledge of the reader.

criteria ("reference value") for fidelity at each representation level are determined in part by the cognitive and socioemotional goals of the reader. Resources are differentially allocated to these different levels of representation so that the reader satisfies these criteria (in a good-enough sort of fashion). Because textbase construction is relatively resource-intensive and typically more associated with cognitive goals (rather than socioemotional goals; Carstensen et al., 2006), the textbase representation constructed by older readers may have reduced fidelity. Because the situational/discourse level is often less resource-intensive and is often more integral to the experience of emotional satisfaction from text, older readers often show better representational fidelity on this dimension. Age differences in representational fidelity for the textbase and discourse levels, then, are postulated to derive from a combination of declines in mechanics and knowledge growth, on the one hand, and an allocation policy (shaped in part by a shift in the motivational status for cognitive activity) in which the reference value for the discourse representation is heightened relative to that for the textbase representation.

Support for this model comes in part from measuring reading time relative to performance. Contrary to what one might expect from theories of generalized slowing (Salthouse, 1996), older readers do not always read more slowly than the young (Ratner, Schell, Crimmins, Mittelman, & Baldinelli, 1987). While older readers sometimes allocate less time to semantic processing of the textbase (Radvansky et al., 2001; Stine, 1990; Stine-Morrow et al., 1996; Stine-Morrow et al., 2004), they very typically do allocate attention to situational shifts (Morrow et al., 1994; Radvansky et al., 2001).

4.3. Some Recent Findings

4.3.1. Word, Textbase, and Discourse Levels Can Be Dissociated in Behavior

Even though allocation to word (surface form) and textbase (semantic content) representations can be operationalized as distinct constructs (see Figure 1), allocation to these two different levels of analysis are often highly correlated (Stine-Morrow et al., 2001, 2008), leaving open the question as to whether readers really can independently regulate these systems. We (Gao, Noh, Eskew, & Stine-Morrow, 2008) recently conducted an experiment that attempted to dissociate these levels not only for the sake of testing this assumption in the SRLP model, but also to (potentially) examine implications of age-related loss of visual acuity for reading processes. According to the Effortfulness hypothesis (Wingfield, Tun, & McCoy, 2005), sensory loss can decrease the quality of encoding by distracting attention needed to decode a muddy sensory array. We tested this in the context of reading by asking college-aged students to read sentences embedded in varying levels of dynamic visual noise in a self-paced fashion using the moving window method. Word reading times were regressed onto word-level features (number of syllables, log word frequency) and textbase features (the introduction of a new concept, sentence boundaries). We expected allocation to word processing to increase with visual noise, and if the Effortfulness idea is correct, allocation to textbase processing should decrease. That is exactly what we found. Figure 2 presents the allocation indices for word and textbase processes (as average z-scores) as a function of level of visual noise (none, low = 50% pixels randomly assigned to a new grayscale value, high = 70% pixels randomly assigned). This crossover interaction shows very nicely the tradeoff in attention between of the different levels of analysis.

To test the idea that understanding text relies on distinct textbase- and discourse-level processors and that older adults depend more on the latter, Shake, Noh, and Stine-Morrow (2009) asked younger and older readers to learn about a single topic by reading a set of sentences that varied in elaboration (from simple factoids to highly elaborated and rich descriptions) and whether or not the sentences were blocked by elaboration (i.e., all the factoids together, and then all the highly elaborated descriptions together; or mixed). The reasoning was that the simpler sentences, like factoids that

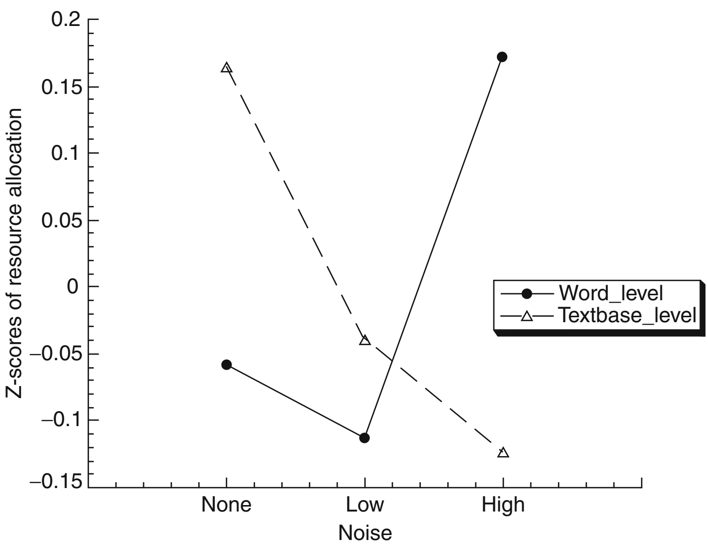

Figure 2 Allocation of attentional resources to word-level (orthographic decoding and lexical access) and textbase-level (conceptual processing) processing as a function of visual noise in the text display (Gao, Noh, Eskew, & Stine-Morrow, 2008). With increasing visual noise, more attention is allocated to decode the muddy surface form, but at a cost to attention available to create an elaborated textbase representation of content.

depend on encoding simple associations, would depend more on the textbase processor to bind sentential elements, but that with more elaboration the discourse-level processor would be more involved. We manipulated whether or not sentences were blocked by elaboration because we reasoned that blocking would allow more consistent engagement of a one processor or the other, but the mixed presentation would require the reader to switch between processors on the fly in an unpredictable fashion. As predicted from the SRLP model, in recalling information about the topic, younger adults were more likely to generate information from the factoids, while older adults recalled more information from the highly elaborated sentences. These effects were also mirrored in accurate memory monitoring, further supporting the idea that age differences arise from effective self-regulation of these systems. Interestingly, the mixed presentation was particularly damaging to the older adults' recall performance, but had very little effect on the memory performance of the young. So even though older adults showed good text memory when passages were elaborated, the interspersed factoids tended to disrupt their performance, presumably because of the additional resources needed to engage and disengage these processors (analogous to task switching; Gopher, Armony, & Greenshpan, 2000).

Data from these studies are consistent with the idea that learning from text depends on three different processors that are independently regulated (see Figure 1). Age-related sensory loss can consume attentional resources needed for textbase understanding, thus compromising what is retained. The textbase processor, which is essentially designed to encode associations (via thematic role assignment from the parser), is especially resource-intensive. Older readers are more likely to rely on the discourse processor when possible.

4.3.2. Strategies to Engage More Specific Encoding of the Textbase

Some of our earlier work has shown that, in contrast with younger adults, older adults tend to allocate time for wrap-up (peaks in reading time reflecting conceptual integration; Aaronson & Scarborough, 1976; Just & Carpenter, 1980), more at clausal boundaries than at sentence boundaries (Miller & Stine-Morrow, 1998). This age difference has been found to be exaggerated among readers with high levels of recall (Stine, 1990). We have speculated that this might be due to a strategy of smaller input cycles that would accommodate a reduced working memory capacity. This assumes that early wrap-up would reduce the processing load of conceptual integration for the whole sentence. Shake, Noh, Hindin, and Stine-Morrow (2007) tested this in an eye-tracking experiment in which wrap-up was induced early through increasing the salience of early boundaries (e.g., *The athletes tried out for a national team in the gym for a chance to earn a position* vs *The athletes tried out for a national team in the gym. They worked hard to earn a position*).

In fact, early boundary salience increased wrap-up and tended to reduce the processing load downstream.

Even though reliance on the discourse processor can be effective and even allow older readers to achieve good performance while largely circumventing the textbase processor (Stine-Morrow et al., 2004), there are certainly times when a distinctive encoding of the textbase (e.g., learning novel associations; factoids) is handy. So one question is whether older adults can be encouraged to do this more specific encoding. Stine-Morrow, Noh, and Shake (in press) investigated this question by providing explicit instruction in conceptual integration. In two reading sessions a week apart, younger and older adults read short passages for delayed cued recall using a moving window method. The first session was a control session at which participants were instructed to read ‘‘naturally.’’ At the second session, these individuals were randomly assigned to an experimental group, who received explicit instruction in making conceptual links as they read, or a control group, who were simply encouraged to allocate effort to reading. Regression analysis of word-by-word reading times was used to isolate the resources allocated to process new concepts as soon as they were encountered (‘‘immediacy’’) or to integrate new concepts at the end of the sentence (‘‘wrap-up’’) while controlling for the demands of lexical processing (e.g., word length and familiarity). The critical test of whether the intervention was effective was a time by condition interaction such that the experimental group would show a greater increase in conceptual processing across sessions than the control. As shown in Figure 3, the intervention was effective in increasing attention to new concepts for both age groups; however, the way in which younger and older adults responded to instruction was very different. While younger adults increased conceptual processing at sentence boundaries only, older adults were more likely to engage an immediacy strategy in which they processed new concepts more thoroughly as they occurred. This might be a sensible solution assuming that working memory capacity is more limited, making it more difficult to maintain activation of multiple concepts.

Allocation to new concepts was predictive of subsequent recall, but the correlation was small; not only was wrap up related to recall, but importantly, change in wrap across session was related to change in recall performance, suggesting that the intervention was effective in both changing processing and changing recall. However, recall within the older group was not as well predicted by attention to new concepts (see also Stine-Morrow et al., 1996, 2008) or by change in attentional allocation to textbase processing. This is interesting because it suggests that even when older adults can be induced to produce something like the textbase reading strategies of the young, this mode of processing is not as effective. Note that the measure of memory performance was delayed recall of content, measured as the proportion of propositions from the original retained in the

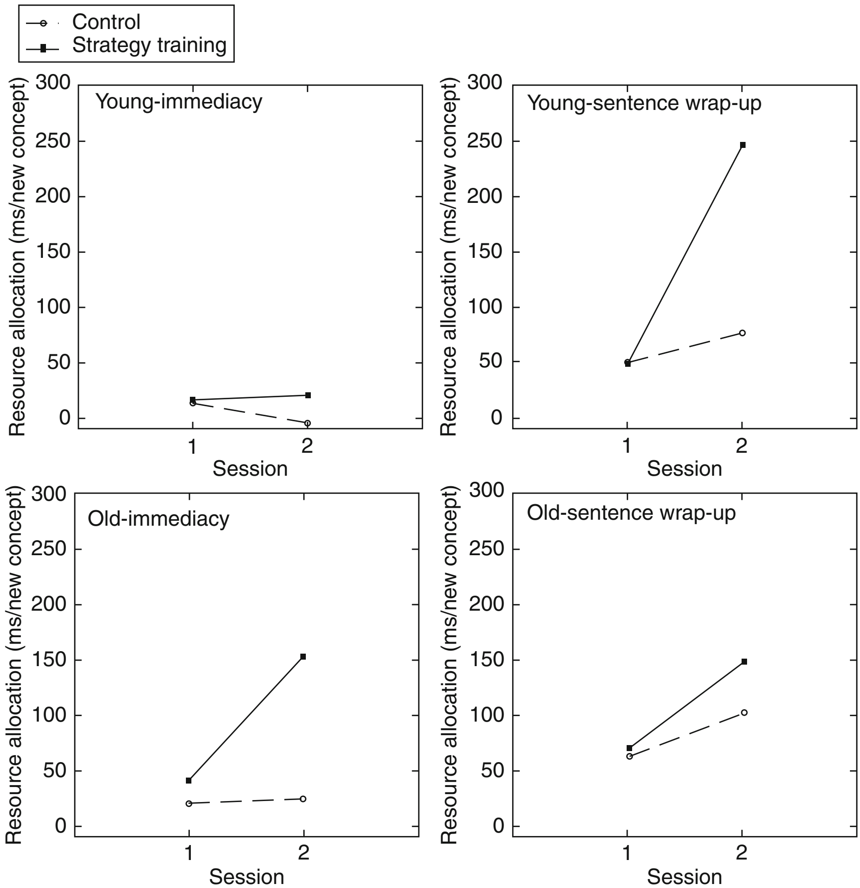

Figure 3 Allocation of attentional resources to immediate processing of new concepts (left panel) and integrative processing of new concepts at sentence boundaries (right panel) for young adults (top panel) and older adults (bottom panel). Participants randomly assigned after Session 1 to receive explicit instruction to pay attention to how new ideas in the text fit together differentially increased their conceptual processing at Session 2, though the primary locus of processing differed as a function of age (data from Stine-Morrow et al., in press).

recall protocols. It may be that the older adults were able to encode the content but that the representation was more fragile and so decayed more quickly.

In his dissertation, Shake (2009; Shake & Stine-Morrow, 2008) has used eye-tracking to illustrate how older adults reread (as measured by regressive eye movements) to compensate for a more fragile and underspecified representation. Younger and older adults read sentences such as, *The mechanic considered herself/himself an expert on foreign cars*. Both age groups showed longer reading times when the reflexive pronoun was inconsistent with the gender stereotype (for those who are fortunate to be oblivious to such things, that would be *herself*), but the locus of such effects was different for young and old. Younger readers showed longer initial gaze durations on the reflexive pronoun when their expectancies were violated. Older readers, who did not show the effect on initial gaze duration, dealt with the inconsistency by immediately regressing to earlier words in the sentence before moving forward in the text (as measured by an effect of expectancy on go-past times). In other words, the expectancy violation gave both age groups pause, but because the surface representations of younger readers have good fidelity, they could resolve the problem without reexamining the text; older adults, by contrast, did not linger on the troubling word, but rather immediately backtracked to resolve the problem. Interestingly, there was age equivalence in go-past times, suggesting that the time younger and older adults needed to completely resolve the anaphoric expression was similar, but the manner in which they achieved resolution was different. Older adults may respond in such a way because they cannot actually retrieve the referent (two words prior), or because they are simply in the habit of not relying on memory in such repairs. (So if the earlier text disappeared as in the moving window method, perhaps they would show the same slow down on the critical word and be able to make the repairs in coherence; this is reminiscent of findings from Touron and Hertzog (2004), showing that older adults tend to look up information (in a word-pair lookup task) rather rely on retrieval (which would be faster) even though when pressed to do so, their retrieval was very good.)

4.3.3. The Role of Crystallized Ability in Regulating Reading

Age-related growth in knowledge may enhance self-regulation of effort to construct a text representation. For example, age-related increases in verbal ability appear to engender greater attention to conceptual integration (Stine-Morrow et al., 2008).

Differences in the ways in which knowledge can affect online text comprehension were examined in a study assessing the effects of new information on reading short mysteries (Miller & Gagne, 2008). Participants received one of three types of information prior to rereading the mysteries: no new information, a part of the solution (a hint), and the full solution. The partial solution was used to represent a situation in which readers have knowledge that must be unpacked or assembled in order for it to be used (Britton & Tesser, 1982; Miller, 2001, 2003; Miller et al., 2004). In contrast, the full-solution condition was used to represent reading when one has relevant information that is assembled and ready to use. Results showed that younger and older readers were similarly facilitated when information was complete and prepackaged (i.e., full solution). However, when information was incomplete (i.e., partial solution), older allocated more time to organizing and integrating information in the text when rereading the mystery relative to when they were rereading with no additional information. In contrast, younger adults showed the expected rereading facilitation in both prior information conditions. Presumably, this additional time allocated by the older readers in the partial solution condition reflected more effort directed to generating inferences and integrating concepts so as to resolve the mystery based on the hints provided in the partial solution. Interestingly, among the old (but not among the young) this additional time allocation was predictive of problem-solving performance.

Other work has shown that experts are better able to focus effort on problem-relevant information in reading about problems in their domain (Morrow, Miller, Ridolfo, Magnor, Fischer, et al., 2008). Younger and older novice and expert pilots read at their own pace a series of scenarios describing problems that can occur while piloting a commercial aircraft. Individuals were asked to identify the problem and the solution, and to answer comprehension questions about details of the scenario across two levels of scenario complexity: high and low. Older experts elaborated more in the problem identification task than younger ones, but older novices elaborated less than their younger counterparts (an age by expertise interaction). Resource allocation measures showed age constancy within both expertise groups, however, novices and experts allocated attention as they comprehended the scenarios very differently. For complex scenarios, experts allocated more time to reading information critical to the problem than did novices, whereas novices allocated more time to word decoding processes, suggesting that experts were allocating attention to the situation model of the problem while novices were focused on more superficial levels of analysis. Importantly, across expertise groups, allocation of reading time to critical regions was positively correlated with comprehension of complex scenarios. These findings suggest that knowledge and experience enable readers to strategically allocate attention to the important elements of the text, regardless of age.

However, there is also evidence to suggest that the effects of knowledge can become stronger with age. Miller (2009a) presented short texts about cooking (procedural texts (more commonly referred to as "recipes") and expository texts) to adults varying in age and cooking knowledge. Although few age differences were evident in reading time and text memory as a function of knowledge, when these measures were combined to create a measure of reading efficiency (time per unit of recall), group differences were found. Specifically, older adults, but not younger adults, increased in efficiency with increasing knowledge (see Figure 4). This age-by-knowledge interaction suggests that the combination of age and expertise engenders a regulatory efficiency such that older adults reading in their domain of expertise may strategically select information for processing that will yield a relatively high return on time invested in reading. That is, older adults may

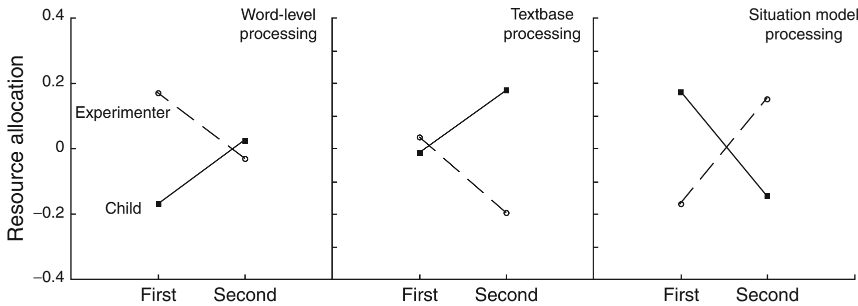

Figure 4 **Resource allocation to word, textbase, and situation model representations at reading (first) and rereading (second) as a function of socioemotional goal (recalling the story to an experimenter as opposed to telling the story to a child) (data from Noh et al., 2007).**

not necessarily "raise the bar" on level of recall desired (i.e., the fidelity of textbase encoding) when they have knowledge at their disposal, but rather capitalize on what they know to allocate attention specifically to the situational representation (Morrow et al., 2009) which can facilitate textbase processing (e.g., Miller & Stine-Morrow, 1998; Wiley & Rayner, 2000). Although a three-way interaction among age, knowledge, and working memory span was nonsignificant, a significant knowledge by working memory span interaction showed at least some evidence that knowledge may reduce demands on working memory, enabling a more efficient approach.

Greater support for the notion that knowledge may be particularly beneficial for those with a smaller working memory capacity was found in a study examining age differences in the effects of schematic knowledge on reading efficiency (Miller, Cohen, & Wingfield, 2006). A passage title manipulation was used (cf. Bransford & Johnson, 1972) such that half of the participants received passage titles prior to reading the passages and half did not. Without the titles, the passages were vague and difficult to understand because the schema connecting the information in the text was absent. In addition, reading difficulty was manipulated such that, in the difficult condition, readers performed a secondary task (pressing a button upon hearing a tone) for half of the passages. Results showed that knowledge effects on reading efficiency were most pronounced among low-knowledge, low-working memory span older adults in the difficult reading condition. These data are consistent with other research showing that the benefits of knowledge are greater among those with a smaller working memory capacity (Sohn & Doane, 2003) and suggest that knowledge reduces demands on working memory.

Other research, however, indicates that the relationships among age, working memory, and knowledge may be more complex than this. Hambrick and Engle (2002) found that those with a larger working memory capacity showed greater increases in performance than did those with a smaller working memory capacity as a function of knowledge. More recently, Hambrick and Oswald (2005) found that working memory capacity and knowledge have positive but independent effects on memory performance. It could be that the effects of knowledge on online encoding measures (such as efficiency) are more likely to show greater advantages of knowledge for low-working memory individuals whereas memory measures alone are more likely to show comparable or increased advantages for high relative to low-working memory individuals. Knowledge may reduce text-encoding demands, but recall may require some threshold of working memory resources for knowledge to be advantageous. However, more research is needed to disentangle working memory and age on the one hand, and processes that may be differentially sensitive to age, knowledge, and working memory on the other.

In general, the research above suggests that the effects of crystallized knowledge (both verbal and domain) on the ability to regulate text understanding may in part account for the resilience in text memory for aging professors (Shimamura, Berry, Mangels, Rusting, & Jurica, 1995).

4.3.4. Managing Multiple Characters in Narratives

Older readers may also manage the construction of the situation model differently. Noh and Stine-Morrow (2009) asked younger and older adults to read short narratives in which a character was introduced. Later, the same character was rementioned ("remention" condition), or another character was introduced ("new" condition), or the continuity of the narrative was maintained without explicit mention of any character ("no mention" condition). At that point in the narrative, participants responded to a recognition probe in which the initial character was presented. Both younger and older readers were slower to recognize the original character if a new character was introduced, but older readers were differentially slower in the New condition, suggesting that once a character was backgrounded by another character, it was particularly difficult for older adults to reactivate it. The introduction of another character was critical, however. Younger and older adults were similarly slower in the No Mention condition relative to the Remention condition. In other words, older readers had no trouble at all retaining a character through the course of the narrative (as long as another discourse entity did not appear). One might think about this as a sort of retroactive interference effect, remembering an old character after a reader has learned about a new character.

In a second experiment, we considered the reverse situation, something akin to proactive interference: does a reader have any difficulty encoding a new character when a character already exists in the discourse world? In this case, both younger and older readers experienced interference in encoding the new character, as measured both in terms of reading time for the sentence in which the new character was introduced, and in probe recognition time for the new character several sentences after its introduction. Older adults were similar to the young in the time allocated when the new character was introduced, but they did show especially long recognition latencies for this character. Together, these experiments suggest that older readers may focus more completely on one character to the exclusion of others: older readers had no trouble retaining the initial character (first experiment), and did not accommodate declines in mental mechanics by slowing down with the introduction of the new character, which was subsequently less accessible for them relative to their younger counterparts.

4.3.5. Social–Emotional Motivation Can Enhance Textbase Processing

While text memory is most typically assessed in a research context with purely cognitive goals in mind, there are often occasions in everyday life in which there is a social–emotional context that might motivate effective retrieval, for example, telling a joke effectively often requires a veridical rendition of the textbase content to set up for the punch line. Another case is telling a story to a child, who will be much less entertained by the broad brush strokes of the narrative relative to a full telling complete with the hairy warts on the witch's nose and the gumdrops on her roof. Recall that Adams et al. (2002) found that age differences in recall of Sufi tales were smaller (negligible) when the retrieval context was a child (who really wanted to hear the story) relative to when the retrieval context was an experimenter (who already knew it and was listening to score recall). Noh, Hindin, Radvansky, and Stine-Morrow (2007) considered whether these effects could be accounted for in part by the way attention was regulated while reading. In this experiment, younger and older participants read and reread a series of Aesop's fables for the purpose of either recalling to an Experimenter or retelling to a Child. We replicated the reduction of age differences in story recall in the Child condition relative to the Experimenter condition, though this could not be completely attributed to age differences in engagement with the text. Patterns of resource allocation were different in the Child and Experimenter conditions, but the shift as function of listener was the same for younger and older adults. In the Experimenter condition, the typical rereading effects were found (Millis, King, & Kim, 2000; Millis, Simon, & tenBroek, 1998), a decrease in word and textbase processing and an increase in attention to the situation model. In the Child condition, however, readers showed greater persistence in word and textbase processing with rereading (and a decrease in situational encoding) (see Figure 5). Both younger and older readers, then, appeared to respond to the social demands of the retrieval context by more thoroughly encoding the surface form and the details of the story. Interestingly, this produced age equivalence in recall.

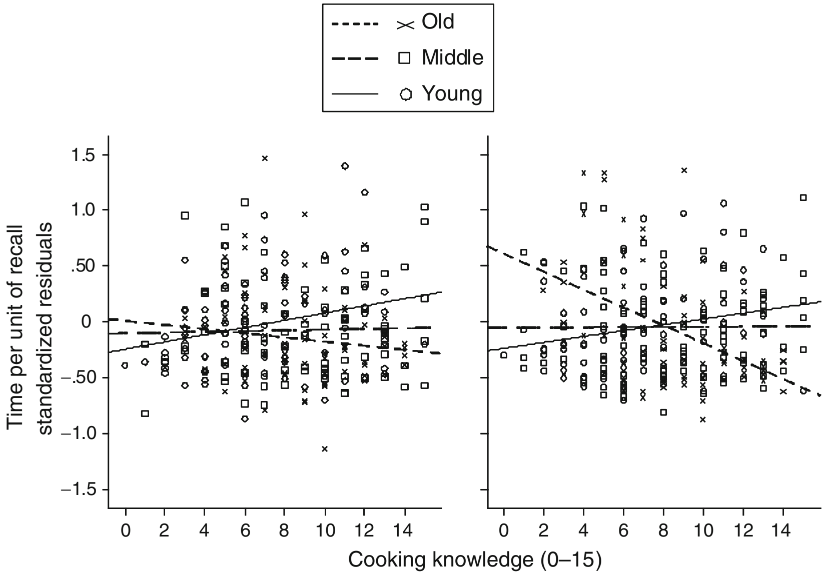

Figure 5 Encoding efficiency (time allocated per proposition recalled, controlling for recall performance and reading time) in reading texts about cooking as a function of age and cooking knowledge (figure from Miller, 2009a).

4.3.6. The Role of Self-Perceptions in Regulating Text Understanding and Memory

Older adults' beliefs about their own capacities for learning and remembering may impact how effort is regulated. For example, older adults who had higher scores on a control beliefs measure allocated more time to difficult texts than did those with lower scores (Miller & Gagne, 2005). Similarly, Stine-Morrow, Shake, et al. (2006) found that age differences in responsiveness to the text demands were accounted for by memory self-efficacy. Together, these data suggest that self-beliefs impact how older adults approach the text in terms of the criterion used to assess changing task demands as well as their willingness to invest in the task in response to the shifting criterion.

In a similar vein, research suggests that older adults may be particularly sensitive to situational factors that affect self-regulation while reading. Miller and West (2009) examined the effects of pre-existing and situational self-beliefs on text comprehension using a false feedback paradigm. Younger and older adults completed a control beliefs measure and then read short mysteries and attempted to solve them. Participants within each age group were randomly assigned to a performance feedback group that received high-performance feedback regarding their problem-solving performance or low-performance feedback. Results showed that high-performance feedback increased self-efficacy of young and older adults alike. However, the effects of feedback on attentional processes were more complex. The effects of positive feedback on older adults depended on their pre-existing levels of control beliefs such that older adults who had high levels of control beliefs allocated more attention to the text than did their low-control peers. These findings suggest that positive feedback may encourage older adults to engage more fully in a reading task, however, only when they possess a strong sense of control.

5. Conclusions

Language processing is often cited as an example of an area of cognition that is immune from age-related change. That is clearly not the case. We have argued that there is a tendency with aging to create an under-specified representation of syntactic form and propositional content that is driven by a combination of declining executive control and attentional resources (Braver & West, 2008) and a developmental shift in motivation for cognitive engagement (Isaacowitz, Charles, & Carstensen, 2000). At the same time, situation model processing is relatively preserved, in part because it depends more on knowledge-based processing (a strength of later adulthood) and because this level of representation is consistent with a developmental social–emotional shift.

Enhanced attention to situation model and discourse-level analysis is not to be confused with a tendency toward gist processing (Kensinger & Schacter, 1999; Koutstaal, Schacter, & Brenner, 2001). An underspecified textbase implies gist-based (fuzzy) processing of propositional content. By contrast, situational and discourse analysis may be completed with a high level of fidelity. We also do not wish to argue that a shift toward situation–priority is always simply a compensatory strategy for textbase decline. Development of a situation model is a skilled activity, which may serve a compensatory function, but may also drive a decreased reliance on more veridical forms of representation. This may run counter to the notion of scaffolding (Park & Reuter-Lorenz, 2009), in which a frontal shift in activation is viewed as compensatory for loss of core networks. The existence of neural plasticity through adulthood (Draganski, Gaser, Busch, Schuierer, Bogdahn, et al., 2004; Draganski, Gaser, Kempermann, Kuhn, Winkler, et al., 2006; Willis, Tennstedt, Marsiske, Ball, Elias, et al., 2006) implies both the capacity for gain with activity and attentional engagement, but also for loss of networks that are not engaged. Thus, we leave open the possibility that skill- and knowledge-based augmentation of some networks may actually drive decline in younger forms of thought.

Language processing is a self-regulated function in two senses. First, we allocate attentional resources selectively to representational forms that are consistent with immediate and long-term goals. Second, in regulating attention through reading to build crystallized ability through the lifespan (Stanovich, West, & Harrison, 1995) and perhaps executive control (Bialystok et al., 2007), we shape our capacity to approach text in the long run.

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CHAPTER NINE

Toward a Comprehensive Model of Comprehension

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Contents

Abstract

The goal of this chapter is to provide the foundation toward developing a more comprehensive model of reading comprehension. To this end, seven prominent comprehension models (Construction–Integration, Structure-Building, Resonance,

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Event-Indexing, Causal Network, Constructionist, and Landscape) are described, evaluated, and compared. We describe what comprehension models have offered thus far, differences and similarities between them, and what comprehension processes are not included within any of the models, and thus, what should be included in a *comprehensive* model. Our primary conclusion from the review of this literature is that current models of comprehension are not necessarily contradictory, but rather cover different spectrums of comprehension processes. Further, no one model adequately accounts for a wide variety of reading situations that have been observed and the range of comprehension considered thus far in comprehension models is too limited.

1. Introduction

1.1. Some Background, Our Purpose, and Our Approach

Comprehension, arguably the backbone of cognition, is the processing of information to extract meaning. It is a complex cognitive process that is necessary for virtually all higher-level cognitive activities, including learning, reasoning, problem solving, and decision making. Comprehension is necessary for the formation of durable memories for events (e.g., Bransford & Johnson, 1972) and has substantial implications regarding our subsequent decisions and actions involving information depicted in events, text, or films (Trabasso & Bartolone, 2003). Further, effective and creative problem solvers have been shown to spend considerably more time comprehending a problem before enacting solutions than less effective problem solvers (e.g., Csikszentmihalyi & Getzels, 1971; Gick & Holyoak, 1983). Comprehension has even been linked to affective response in the context of art appreciation (Millis & Larson, 2008).

Despite the importance of comprehension across a variety of areas of study in cognitive psychology, it has primarily been investigated in the context of text and discourse comprehension (see Graesser, Millis, & Zwaan, 1997 for an extensive review). And, text and discourse researchers have particularly focused on comprehension of text, as opposed to other mediums. This focus is at least partially influenced by the fact that texts provide a convenient modality for presenting stimuli. However, interest in the study of text comprehension is not merely a matter of convenience. Text comprehension is heavily studied because reading is a ubiquitous activity and central to functioning in an industrialized society. In addition, text comprehension is informative of cognition in general. First, text comprehension is complex and supported by a variety of lower and higher-level processes (Balota, Flores d'Arcais, & Rayner, 1990). Although many of these processes (and in particular lower-level processes such as orthographic processes, decoding) may be unique to reading, other processes are relevant to comprehension beyond the medium of text (Magliano, Radvansky, & Copeland, 2007). Moreover, many of the theoretical debates address central issues in cognition, such as the extent to which cognitive processes are modular versus interactive (e.g., Fodor, 1983; Marslen-Wilson & Tyler, 1987) and the extent that comprehension is supported by bottom-up versus effortful processing (e.g., Albrecht & Myers, 1995; Graesser, Singer, & Trabasso, 1994; Magliano & Radvansky, 2001; McKoon & Ratcliff, 1998; Myers & O'Brien, 1998). As such, we contend that the text comprehension literature and theories should be of interest to many researchers, including those outside the study of text comprehension per se.

It has been approximately 30 years since the first major processing model[1] of comprehension was proposed by Kintsch and van Dijk (1978), providing a foundation for most subsequent models. Despite the fact that many theories of text comprehension can be traced back to the seminal theory proposed by Kintsch and van Dijk (1978), expert and casual readers of this literature will agree that the theoretical landscape is quite complex. For example, in this chapter we discuss seven prominent models of comprehension, and we can assure the reader that we have left out numerous others from our discussion out of necessity. As one might expect, many of the models have been pitched against each other and as mutually exclusive (e.g., Albrecht & Myers, 1995). As is necessary for a science to grow, there has been a great deal of debate and a host of controversies in the field of discourse comprehension over the past several decades. And, like all fields of science, these debates have been both constructive and destructive. Indeed, it may be difficult for a budding researcher in this area to discriminate amongst the models and determine which is most relevant to address critical research questions of interest.

Upon reflection, we have come to the conclusion that the theoretical landscape is complex because researchers have focused on different aspects of discourse comprehension, different kinds of discourse (expository vs narrative), different kinds of reading situations (e.g., reading to learn for a course vs casual reading), and different sources of individual differences in comprehension. We believe that the time is ripe to reconsider the major and influential models of discourse comprehension with the goal of formulating a comprehensive theory of discourse comprehension. We consider the research in this field sufficiently mature to work toward a more comprehensive model of comprehension: a model that explains the full scope of comprehension processes. A first step toward such a model is to understand

[1] We use the term *model* rather than systematically distinguishing between models and theories. A model is usually used to refer to a theory that is implemented computationally, whereas a theory is usually used to refer to a verbal explanation of a set of phenomena. Here, however, we use the term model to refer to all seven theories that we consider, even though only a few of them are implemented computationally.

what comprehension models have offered thus far, what are the differences and similarities between them, and what comprehension processes are not included within any of the models, and thus, what should be included in a comprehensive model.

Our approach to this task relies on two devices. The first is a depiction in Figure 1 of potential comprehension situations. Figure 1 crosses the reader with the text in terms of the level of strategic or active reading expected by the reader and the ease of processing afforded by the text. Reading comprehension will tend to be best in quadrant A, where the ease of processing is high and the reader is strategic, and worse in quadrant D, where the ease of processing is low and the reader is not strategic. Comprehension will tend to be more superficial and thematic in quadrant B, and will tend to be limited more to a textbase-level understanding (i.e., a representation that primarily reflects the explicit content presented in the text) in quadrant C. Of course, these comprehension states are a function of a multitude of factors. For example, the ease of processing a text can depend on the familiarity of the words, the complexity of the domain, text readability, text cohesion, text domain or genre, and a multitude of other factors, some of which interact with one another. Similarly, the likelihood that a reader will engage in strategic comprehension processes can depend on reading skill, comprehension skill, motivation, metacognitive awareness, domain knowledge, reading strategy knowledge, goals, and tasks, which in turn can interact, not only with one another but also with characteristics of the text.

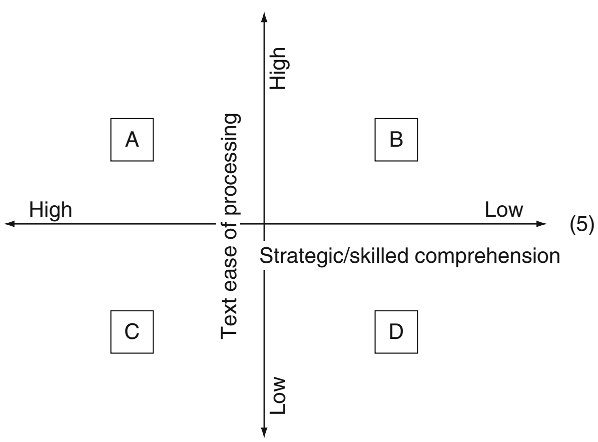


Figure 1 Four quadrants crossing the difficulty of the text and the degree to which the reader engages in strategic or skilled comprehension processes. The four quadrants describe the scope of comprehension situations to be accounted for by comprehensive comprehension models. Comprehension will tend to be best in quadrant A and worse in quadrant D. It is likely to be more superficial and thematic in quadrant B and dominated by a textbase level of understanding in quadrant C.

Despite the complexity of the factors that contribute to the four states depicted in Figure 1, it provides a platform for analyzing the foci of the comprehension models under consideration by considering each one across the four quadrants. By doing so, our contention is that we can develop a better understanding of the differences between current comprehension models and where we need to go in terms of developing more comprehensive models of comprehension.

The second device we use to evaluate comprehension models is a list of dimensions that vary in importance or inclusion between the models. We discuss those dimensions in Section 3 after we have described the seven comprehension models under consideration in Section 2. We then summarize our major conclusions from Sections 2 and 3 in Section 4. Then, in Section 5, we discuss issues that need be considered by a more comprehensive model of comprehension.

Our overarching purpose here is to better understand the theoretical assumptions that have been made by comprehension models and to identify necessary, unnecessary, and missing dimensions. There have been many comprehension models proposed over the last several decades, far too many to review here. Hence, to narrow the task, we focus here on seven models that have received the most attention, at least by text and discourse researchers. The seven theories that we discuss include three that have attempted to describe basic and overall comprehension processes: the *Construction–Integration* (CI) model (Kintsch, 1988, 1998); the *Structure-Building* model (Gernsbacher, 1997; Gernsbacher, Varner, & Faust, 1990); and the *Landscape* model (Linderholm, Virtue, Tzeng, & van den Broek, 2004; Tzeng, van den Broek, Kendeou, & Lee, 2005; van den Broek, Rapp, & Kendeou, 2005; van den Broek, Young, Tzeng, & Linderholm, 1999). We also describe four accounts that have centered primarily on the processes of going beyond the information in a target sentence, such as the retrieval of prior knowledge and inferential processes. These include the *Resonance* model (Albrecht & Myers, 1995; Myers & O'Brien, 1998; Myers, O'Brien, Albrecht, & Mason, 1994), the *Event-Indexing* model (Zwaan, Langston, & Graesser, 1995), the *Causal Network* model (Langston & Trabasso, 1999; Suh & Trabasso, 1993; Trabasso & Suh, 1993; Trabasso & van den Broek, 1985; Trabasso, van den Broek, & Liu, 1988; Trabasso, van den Broek, & Suh, 1989), and *the Constructionist* model (Graesser et al., 1994).

1.2. Comprehension: Some Basics

Comprehension is necessary for processing essentially all information that we encounter. Information is conveyed via a wide sort of media: in our surroundings, through conversations, in pictures, in video, and of course text. Though we comprehend through a wide variety of media, models of comprehension have focused on processes involved in understanding written text. This focus can be attributed to written text being a media that is more easily controlled, manipulated, and analyzed. Nonetheless, most models assume that their theories generalize to the understanding of information conveyed in discourse, and some hope that their assumptions generalize to the understanding of any media, including visual information. Here, though we refer to understanding of text, it is assumed that the term *text* can refer to written or oral discourse.

Theories of comprehension are universally concerned with the nature of a mental representation that emerges when readers and listeners process larger discourse structures such as stories, informational passages, books, textbooks, and conversations. The process of understanding the words, the sentences, and the relations between the sentences comprises comprehension. Its prerequisite, though not necessarily its precursor, is the decoding and parsing of the information. All comprehension models assume that lower-level processes such as word decoding and syntactic parsing contribute to comprehension, but that these processes are more or less in place at the start of the higher-level comprehension processes described by these models.

Language understanding, including lexical decoding and syntactical parsing, is a relatively separate field of study (e.g., Bock, 1982; Elman, 2004, 2009; Frazier, 1987; MacDonald, Pearlmutter, & Seidenberg, 1994; Tabor & Tanenhaus, 1999). The field of text and discourse picks up after basic language understanding, to explain processes germane to the comprehension of multiple ideas and the relations between those ideas. These processes include understanding the gist or underlying meaning of ideas; the priming (or *unconscious* activation) of related concepts, and the linking of ideas that are explicitly related. When those ideas are not explicitly related or when the comprehender seeks a deeper understanding, then inferences comprise a critical component of comprehension.

Most text and discourse researchers use the term *mental representation* to refer to the outcome of text comprehension processes. The reader's mental representation consists of information from the text, information that is related to the text, and the inferences that are generated. Inferencing is the process of connecting information in the environment (e.g., current sentence of a text) to information that is not in the current environment (e.g., information in the ensuing representation of the text, world knowledge, or episodic knowledge for past events, such as other texts or prior experiences). One type of inference connects current information to information that was previously encountered in the text, such as connecting the current sentence to a previous sentence. These are often called bridging inferences. Another type of inference connects current information to knowledge that is not in the text. For such knowledge-based inferences, the comprehender brings knowledge that is related to the text to the focus of attention, and by doing so, makes connections between the text and prior knowledge. These are often called associative inferences or elaborations. Where text and discourse researchers are divided is on the extent to which inferences are generated and the nature of those inferences. For example, there has been some debate over whether readers generate elaborative inferences that are not necessary for establishing coherence in understanding (e.g., Graesser et al., 1994; McKoon & Ratcliff, 1992).

As shown in Figure 2, these two types of inferences can be thought of as going *up*, or *back*, to prior text (i.e., bridging inferences) in contrast to going *outside* of the text to prior knowledge (i.e., elaborations). Of course, prior knowledge is continuously activated during comprehension: each time a word is encountered, prior knowledge is activated and related concepts are primed. When comprehenders have more knowledge about the domain, or about the world, then their understanding will be more rich and coherent because more concepts are automatically primed. Importantly, many researchers argue that this relatively automatic or effortless process of knowledge activation should not be confused with knowledge-based inferences (or elaborations) (e.g., Kintsch, 1993, 1998). Though, where the line should be drawn between the two is not clear.

1.3. Common Assumptions Across Comprehension Models

In our analysis of the seven models under consideration, we identified eight dimensions of comprehension that appear to be central to all of the models. These dimensions are listed and defined in Table 1. We describe them here because they not only serve to specify a set of cognitive systems and processes that support comprehension, but also this list clearly illustrates that comprehension has important links to other areas of cognition. That is, many of these dimensions are basic components of processing models for other dimensions of cognition.

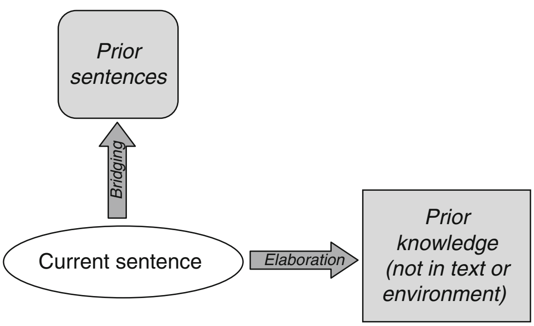


Figure 2 Inferences can be *up* to prior text, called bridging inferences, or *out* to prior knowledge, called elaborations.

Table 1 Eight Dimensions of Comprehension Models that are Either Important or Central to the Seven Comprehension Models Discussed Here

1. **Connectionist architecture.** Following connectionist assumptions, most models assume that comprehension involves the parallel activation of information in the environment (e.g., words in the text), the underlying meaning of that information, and prior knowledge. Activation sources are often represented as layers in a network of nodes and links, with nodes representing words, propositions, or concepts, and links representing the relationships between them (e.g., predicates, verbs, causal connections).
2. **Spreading activation.** This is the notion that the activation of concepts spreads activation to related concepts, resulting in a change in their activation. Current models generally assume some sort of retrieval mechanism that determines what information is initially activated or available. Spreading activation is applied to the available concepts in memory, and this process changes the activation of concepts depending on their connectivity and initial strengths in the representation.
3. **Automatic unconscious processing.** Virtually all models assume that some information is available automatically during reading, and that there is some level of processing that is not consciously available to the reader. However, the nature of automaticity, which comprehension processes are automatic or unconscious, and the effects of unconscious processing is debated between models.
4. **Discourse focus.** Comprehension models commonly assume that there is an attentional focus by the reader and this focus changes across time and as the input changes. The memorial strength of concepts and ideas is in part related to the amount of attentional focus they receive during encoding.
5. **Convergence and constraint satisfaction.** Comprehension models generally assume that the activation of any given concept or idea is based on the degree to which it receives activation from related concepts and ideas. The mental representation is constrained by activated concepts and the relations between concepts in the input, as well as by information available from long-term memory.
6. **Mapping.** This is a general term to refer to processes to establish how the current linguistic input is related to the prior context. Mapping is influenced by referential and situational cohesion. It is likely an unconscious activity, but the product can be consciously available to the reader. A sense of continuity emerges from the mapping process. When mapping fails, the reader may be induced to generate inferences.
7. **Text-based inferencing.** This refers to making inferences that establish connections between discourse constituents (or bridging inferences). These inferences can result when mapping processes encounter referential or situational cohesion gaps. Relationships between ideas in the text must be inferred when explicit cues such as argument overlap and connectives are absent. These inferences may be considered part of the situation model to the extent that they reflect causal, motivational, temporal, and spatial relationships.
8. **Memory constraints.** Comprehension models generally assume that working memory capacity is limited. Some models of comprehension have adopted an information processing perspective wherein working memory and long-term memory are separate and working memory capacity is limited. Other models have adopted the long-term working memory perspective wherein recently activated or highly familiar information is quickly available from long-term (working) memory.

An overarching aspect of these comprehension models is that they all implicitly or explicitly assume that an underlying (1) *connectionist architecture* describes the nature of the memory representation for texts, wherein there are nodes and links, and these vary in strength. This aspect of theories of comprehension is important because it moves away from the early information-processing approach (e.g., Atkinson & Shiffrin, 1968; Baddeley, 2001) that assumes that short-term memory (or working memory) and long-term memory are separate, and toward models that assume that the focus of attention during reading comprises an activated state of long-term memory (see Healy & McNamara, 1996 for a review of memory models). Connectionist architectures assume parallel activation of concepts such that multiple concepts can be activated at the same time. They further assume that concepts are conscious to the extent that they are activated in memory. As such, some concepts may be activated below threshold, and thus primed, but not consciously available without additional stimuli.

Dimensions 2–7 in Table 1 essentially fall out of connectionist architectures. The second common assumption is that there is (2) *spreading activation* between concepts that are related or linked within the representation. Thus, when a concept is activated, its activation spreads and potentially primes (i.e., lowers the threshold) or activates related concepts.

A third assumption is that many processes that support comprehension are (3) *automatic or unconscious* to the reader. Readers are for the most part consciously aware of the products of comprehension, many of which are a result of the spread of activation (as will be more apparent when we discuss specific models of comprehension). This is not to say that readers are aware of all knowledge that is activated through a spread of activation. Although many concepts may be activated (or near threshold) in memory, only a subset may be consciously available in the reader's attention or focus at any one point in time. As such, these models assume that there is a focus of attention, or (4) *discourse focus*. Reading is an inherently goal-directed activity and like many such activities, readers have control over their attentional resources. Those aspects of the discourse that are most relevant to a reader's goals will be in the discourse focus. For example, if a reader is attempting to locate specific information in a text necessary to write a paper, content that semantically overlaps with the topic of the paper will be in the discourse focus more than information that is deemed less relevant.

The fifth common dimension of comprehension models is that what comes into focus is at least partially a function of (5) *convergence* and *constraint satisfaction*, such that the activation of a concept is determined by its relation to other concepts. Concepts that are related to other concepts in the discourse will receive more activation, and thus will be more memorable. This convergence of activation is the result of spreading activation. That is, related concepts spread activation to each other, and therefore, concepts with more connections to other concepts receive more activation.

The concepts with the greatest amount of activation become *conscious* and more memorable. Those with few connections recede from consciousness, or the discourse focus, and tend to be less memorable.

Sixth, researchers agree that there are connections made between incoming and previously activated concepts, which is often referred to as (6) *mapping*. Seventh, when mapping fails, there is a process of generating *inferences*. Common to all models is the assumption that readers make connections between text constituents, inferring causal, spatial, and temporal relationships. These relationships are generally assumed to be established via a process of generating (7) text-based inferences. Virtually all theories of discourse comprehension describe the process of establishing coherence in understanding and as such, it makes sense that these processes are central to most theories.

The eighth assumption regarding (8) *memory constraints* does not necessary fall out of connectionist architectures. In fact, an information-processing perspective, postulating a separate working memory and long-term memory, is somewhat contradictory to a connectionist perspective, which generally assumes that working memory is the activated state of long-term memory. The memory constraints assumed by most comprehension models likely follows from their focus on higher-level (serial) processing of text, rather than the lower-level processes involved in reading, and as a result, comprehension models generally assume that the reader can process only 2–4 idea units or *propositions* at any one time.

2. A Review of Seven Comprehension Theories

In this section, we review seven comprehension models that have dominated text and discourse research over the past decades. We discuss the CI model first because it is the earliest computational model and provided a foundation for the field of text and discourse. The Structure-Building model is described next because, like the CI model, it was intended to be a general model of discourse processing. We then describe the Resonance, Event-Indexing, Causal Network, and Constructionist models, which address specific aspects of discourse processing (e.g., bottom-up processes, top-down processing, the construction of a situation model). Finally, the Landscape model is considered last because it attempts to combine contrasting assumptions from several models.

2.1. Construction–Integration

2.1.1. Overview and Some Historical Context

Kintsch first proposed the basics of the CI model in 1988, and then, in his 1998 book, expanded on the model and proposed a general processing framework for cognition. The CI model is considered to be the most complete and well-formulated model of text comprehension. Also, there is a computational implementation of the model (Kintsch & Welsch, 1991; Mross & Roberts, 1992) that can be used to test its theoretical assumptions as well as contrasting assumptions from other theories.

The CI model built upon the first psychological process theory of discourse comprehension proposed in 1978 by Kintsch and van Dijk (see also van Dijk & Kintsch, 1983). The Kintsch and van Dijk model shifted focus away from descriptions of the memorial representations for text toward the processes that give rise to comprehension (see van den Broek & Gustafson, 1999 for an extensive discussion of the history of discourse-processing research). The Kintsch and van Dijk model was far different from its contemporary, schema-based models of comprehension (e.g., Rumelhart, 1977; Schank & Abelson, 1977), in that it focused on processes and strategies during comprehension. It attempted to describe the iterative processes in mapping current discourse input to the prior discourse context, which is now considered to be central to comprehension. Moreover, Kintsch and van Dijk's model was ground breaking in that it relied on discourse analysis to identify the presence of cohesion cues in the discourse (relationships between sentences) that afford mapping between local and distal discourse constituents.

Although Kintsch and van Dijk's (1978) model was a critical first step, much was left out of this initial model. In 1983, the constructs of *situation* and *mental models* were introduced to the vernacular (Johnson-Laird, 1983; van Dijk & Kintsch, 1983), which led to a profound shift in the focus of discourse-processing theory and research. Similar to early schema theories, these constructs conveyed the critical notion that comprehension is more than deriving relationships between explicitly mentioned discourse constituents. Specifically, it involves generating inferences that lead to the incorporation of relevant background knowledge into the mental representation. Moreover, these constructs conveyed that deep comprehension reflects an understanding of the referenced and implied situations, rather than merely representing explicit content.

The notion of the situation model has become a dominant focus in research on discourse comprehension. Some theories have focused on delineating the inferences that guide the construction of a situation model (Graesser et al., 1994; McKoon & Ratcliff, 1992). Other research has focused on understanding the representational nature of situation models and how they reflect spatial, temporal, causal, and motivational relationships (e.g., Zwaan & Radvansky, 1998). Still others have focused on the extent to which situation models are supported by dumb, bottom-up processes compared to effortful, strategic processes (Graesser et al., 1994; Magliano & Radvansky, 2001; McKoon & Ratcliff, 1998; Myers & O'Brien, 1998; Singer, Graesser, & Trabasso, 1994).

2.1.2. Fundamental Assumptions

Kintsch (1988, 1998) reformulated and instantiated the CI model within a connectionist architecture and thus the assumptions described in Table 1 apply to the CI model. Here, we describe additional assumptions specific to the CI model, noting that it is challenging to describe all of the assumptions germane to a model that has been specified across three books and an uncountable number of experimental tests and demonstrations.

2.1.2.1. Construction–Integration The first aspect of the model is conveyed in its name, Construction–Integration. *Construction* refers to the activation of the information in the text and related knowledge. The construction process includes the initial activation of related knowledge (following principles of priming), including both relevant and irrelevant knowledge with respect to the immediate or intended context. This knowledge activation process is often referred to as *dumb activation* because it assumes that top-down processing does not constrain initial activation of knowledge. It has also been described as *retrieval based*, emphasizing the role of automatic memory retrieval processes in comprehension (Kintsch, 1998, p. 97). For each cycle of input during construction, there are four potential sources of activation. These sources include the current input (sentence or proposition), the previous sentence or proposition, related knowledge, and potentially (though not by default), reinstatements from prior text.

Integration refers to the spreading of activation across the network until it settles (i.e., the activation values for propositions stop changing as a result of spreading activation). This process results in greater activation for concepts that are linked to other concepts, and a loss in activation for peripheral concepts that have fewer connections to other concepts in the mental representation. Interestingly, spreading activation mechanisms are assumed during the integration process, but are not in the construction process (which is assumed to be retrieval based). During integration, activation sources from the construction process are iteratively integrated using a constraint satisfaction process (see Table 1, No. 5). In the CI model, the constraint satisfaction is implemented using vector multiplication followed by normalization (i.e., dividing by the most highly activated concept) until the network settles (i.e., when there is little change in node activation values). The normalization process follows from the assumption that activation resources are constrained by a limited working memory (see Table 1, No. 8); thus, activation is spread through the network, in the end leaving only those few concepts and ideas that are connected to many other concepts, whereas less connected concepts (e.g., those that are less semantically related) lose activation. The resulting *activation patterns* (i.e., the strengths of the nodes and links) from the Construction–Integration process can be viewed *dynamically* across iterations (i.e., as changes within a cycle) or across cycles (i.e., across sentences or propositions), or at the end of processing (i.e., for the entire passage).

2.1.2.2. Levels of Representation The CI model assumes that a sentence that is read comprises three *levels of representation* (Kintsch, 1988, 1998; van Dijk & Kintsch, 1983). The notion of levels within the reader's mental representation has been arguably one of the more influential assumptions of the model. Though other levels of representation have been included in various instantiations of the CI model (e.g., Doane, Sohn, McNamara, & Adams, 2000; Nathan, Kintsch, & Young, 1992), the principal levels are *the surface structure, the propositional textbase*, and *the situation model*.

The surface structure represents the words in the text and their syntactic relations. Each word in the text is represented by a node, and the links between nodes can be used to represent syntactic relations. Notably, the surface structure is often left out of the computational model because it is generally assumed to have little effect on comprehension. Indeed, there is no mention of the surface structure in Kintsch (1998).

2.1.2.3. The Textbase and Propositions The *textbase level* is represented in terms of *propositions*. One important assumption of the model is that the fundamental unit of processing is the proposition, which consists of a predicate and argument(s). The proposition generally represents one complete idea. It represents the underlying meaning of the explicit information in the text, discourse, or scene. For purposes of convention, regardless of the perceptual format of the information (verbal, written, visual), it is represented in the model propositionally. An atomic proposition consists of PREDICATE(ARGUMENT, ARGUMENT), where the arguments fill slots determined by the predicate (e.g., agent, object, instrument, goal). Example 1 comprises a predicate (hand) and three arguments including an agent (he), object (book), and goal (student).

Sentence: He handed the book to the student.
Propositional representation: hand(he, book, student) (1)

Tense and aspect are generally not included in the propositional representation. However, explicit information regarding time and place is represented within complex propositions, which consist of several subpropositions subordinate to a core proposition. The subpropositions can include modifiers as well as information about circumstance, as shown in Example 2 (presented in Figure 3). There are many ways to represent complex sentences propositionally, but this example is representative of a typical approach (see Kintsch, 1998).

Links in the mental representation are conveyed by the predicates and by overlap between arguments. Notably, *overlap between arguments* provides the principal means of connecting ideas. In contrast, overlap between predicates

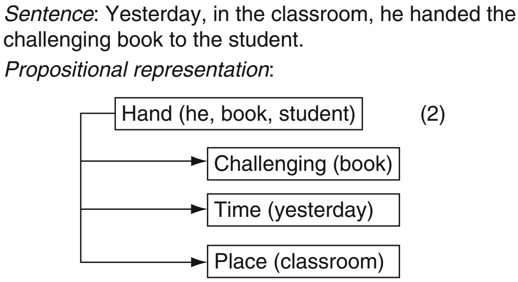


Figure 3 **Propositionalization of a sentence with a main proposition and subpropositions (Example 2).**

(verbs, modifiers) in the CI model does not result in connections between them. For example, the two sentences in Example 3 would be linked via argument overlap (via *classroom*) by default and thus would be more cohesive, whereas the two sentences in Example 4 would not necessarily be connected via the textbase.

Sentence 1: Yesterday, in the classroom, he handed the challenging book to the student. (3)
Sentence 2: All of the other children in the classroom cringed.

Sentence 1: Yesterday, in the classroom, he handed the challenging book to the student. (4)
Sentence 2: She handed it immediately to her neighbor.

Notice that in Example 4, there are no explicit arguments that provide overlap between the sentences. This results in a potential cohesion gap because, even though *handed* occurs in both sentences, overlap resulting from predicates is not included the model. This has theoretical implications concerning the nature of text cohesion; notably that it is driven solely by argument overlap and not by events and actions (Kintsch, 1995; cf. Giora, 1985; Magliano, Trabasso, & Graesser, 1999; Zwaan, Magliano, & Graesser, 1995). Nonetheless, the model would assume that the reader would be likely to make the inference that *she* was the *student* and this inference would connect the two sentences. These types of textual bridging inferences and knowledge-based inferences contribute to the situation model level of representation.

2.1.2.4. The Situation Model and Inferences The situation model includes all inferences that go beyond the concepts that are explicitly mentioned in the text. This construct has arguably garnered the most attention of the three levels of representation proposed by the model in discourse comprehension research since it was postulated in the early 1980s (Johnson-Laird, 1983; van Dijk & Kintsch, 1983). In the past decades, the situation model and textbase representations have often been treated as if they are compartmentalized rather than aspects of the same representation. If this characterization of the literature is correct, it reflects a fundamental misconception. Specifically, the situation model and the textbase should be viewed as different dimensions of the episodic memory for a text, rather than entirely different and separate mental representations of the text content (Graesser & Clark, 1985; Kintsch, 1988; van Dijk & Kintsch, 1983). In fact, as we will describe in greater detail in Section 2.4, the situation model provides one basis for establishing relationships between propositions in the textbase (e.g., Zwaan, Magliano et al., 1995), and thus could not possibly be extricated from it.

Kintsch (1998) classifies the *inferences* that contribute to the situation model level of representation according to whether they are *automatic* versus *controlled* and whether they are *retrieved* versus *generated*. The first dichotomy distinguishes information that is primed by the context (i.e., automatic) and information that is consciously or purposefully activated. This distinction is orthogonal to the differentiation drawn in Figure 2, because both bridging and elaborative inferences can be either (or more or less) automatic versus controlled.

The second dichotomy that Kintsch makes regarding inferences distinguishes information that is retrieved from the current context and information that is generated, going beyond the given information. This distinction more or less aligns with Figure 2, in that bridging inferences rely more on the current context whereas elaborations go beyond the given information.

Kintsch (1993, 1998) argues that only controlled, generated inferences (e.g., controlled, purposeful, or reasoned elaborations) are true inferences that go beyond the information in the text. In contrast, most comprehension researchers consider all four types to be inferences (e.g., Magliano & Graesser, 1991; Singer, 1988). Regardless of what is or is not considered to be an inference, it is generally assumed that connections among ideas in the text and connections to prior knowledge comprise the situation model. If a reader is less active, and activates little knowledge beyond the information in the text, then the situation model is assumed to be less coherent, leaving the reader with a predominately textbase level of understanding.

2.1.2.5. Microstructure and Macrostructure Orthogonal to the notion of levels of representation (e.g., the textbase and situation model) is the microstructure and macrostructure of the reader's representation. The microstructure is driven by local structure of the text whereas the macrostructure is driven by the text's global or hierarchical structure. The microstructure is akin to the propositional representation of the text but it represents the reader's mental representation and thus includes the reader's local inferences. The macrostructure is much the same as the microstructure if the text ideas are ordered serially. However, generally this is not the case and the reader constructs a hierarchical representation of the text. This structure may be relatively explicit in the text, for example as conveyed by headers and topic sentences. But, usually it is up to the reader to infer the global organization of text. This global understanding is often conveyed in terms of the text's *gist* (Kintsch, 1998; van Dijk & Kintsch, 1983).

2.1.2.6. Cohesion, Coherence, and the Situation Model A *coherent* understanding of a text or discourse emerges to the extent that the reader activates knowledge, incorporates that knowledge into the mental representations, and establishes connections between propositions in the discourse representation. Although these processes and outcomes are usually achieved without effort on the part of the reader, it is also assumed that breaks in the discourse (i.e., *cohesion* gaps) induce the reader to activate more knowledge and potentially engage in effortful inferential processes. If the reader can make relatively automatic connections to the prior discourse, then less prior knowledge will be activated. If gaps are encountered, then the reader will activate prior knowledge *to the extent that it is available*.

It is this assumption of the model that led to research by Britton and Gülgöz (1991), which demonstrated that the CI model can be successfully used to guide text revisions by identifying gaps in the discourse. Repairing those gaps by improving argument overlap (i.e., *cohesion*) in the text led to better comprehension in comparison to intuitively guided text revisions. However, the *coherence* of the reader's overall mental representation is most heavily influenced by the situation model. When the reader generates more prior knowledge and when there are numerous connections within the representation, the representation settles more quickly, is more stable, and results in a stronger long-term memory representation.

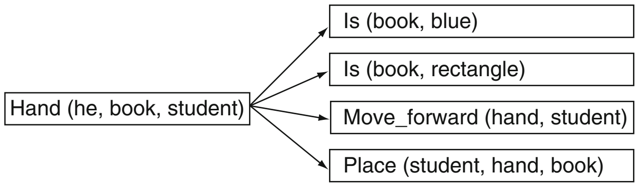
This aspect of the model led to predictions confirmed first by McNamara, Kintsch, Songer, and Kintsch (1996) that *the effects of text cohesion and prior knowledge interact* (see also McNamara, 2001; McNamara & Kintsch, 1996a; O'Reilly & McNamara, 2007a; Ozuru, Dempsey, & McNamara, 2009). These studies show that low-knowledge readers benefit from greater cohesion in the text because they lack the necessary prior knowledge to generate bridging inferences. When the text lacks cohesion, inferences may improve the reader's textbase-level understanding and those inferences may improve the situation model for individual sentences, but the reader is generally unable to generate the knowledge-based inferences necessary to make connections between separate ideas in the text (McNamara, 2004). By contrast, high-knowledge readers (who do not generate strategic inferences; O'Reilly & McNamara, 2007a) gain from the cohesion gaps in the text because they are induced by the gaps to access knowledge to understand the text. Thus, low-knowledge readers gain from high cohesion text, whereas high-knowledge readers gain from low cohesion text.

The theoretical explanation for these *cohesion* effects (for both high- and low-knowledge readers) rests on the assumption that comprehension is largely determined by the *coherence* of the reader's situation model, and this is a function of both the cohesion of the text and the inferences generated by the reader. This assumption is generally accepted by models of comprehension.

What is more in the line of debate is what comprises the situation model. The CI model relies on *argument overlap* as a proxy for other types of *situational relationships* (e.g., causal cohesion) and Kintsch (1995) has argued that argument overlap is sufficiently correlated with other sources of connections. However, others have argued with this contention (Giora, 1985; Magliano, Trabasso et al., 1999; Zwaan, Magliano et al., 1995). They argue that other sources of connectivity in the mental representation are crucial to comprehension, and cannot be sufficiently accounted for via indices of argument overlap.

Nonetheless, what is included in the situation model in the computational implementation of the CI model is generally up to the researcher. That is, more or less knowledge may be assumed and different types of connections can be included. Thus, it is possible to implement other kinds of relationships, particularly if their inclusion is guided by a theoretically based discourse analysis that identifies the presence and absence of situational cohesion (e.g., Magliano, Zwaan, & Graesser, 1999; Zwaan, Magliano et al., 1995).

2.1.2.7. The Proposition Controversy In addition to issues regarding the nature of the situation model and what types of inferences are drawn while reading, there is some controversy regarding the proposition as the sole means of representing ideas within the CI model. Some researchers have questioned the psychological validity of the proposition (Perfetti, Britt, & Georgi, 1995) and, because the proposition is generally considered to be most representative of verbal or symbolic thought, there is particular controversy regarding the importance of nonverbal and nonsymbolic thought such as images and sensory/motor representations (Zwaan, 2004). To accommodate such concerns, Kintsch (1998) acknowledges that ideas may be in the form of verbal, symbolic, iconic, or even embodied thoughts. For example, a reader's situation model corresponding to Example 1 could include associations such as those depicted in Example 5 depicted in Figure 4, which include the shape and color of the book as well as body movements. Kintsch argues that the ideas and relationships captured by propositional representations may reflect virtually any form of mental representations, including symbolic, perceptual, and motoric thought. It is important to keep in mind that no strong claim is made that these notations are analog to the actual mental representations, but rather they serve to represent these constructs within the constraints of the computational simulation. While some theorists may consider this accommodation to be



(5)

Figure 4 **Propositionalization of *He handed the book to the student* including iconic and embodied aspects of the meaning, such as how the book looks and the direction of movement in giving the book (Example 5).**

superficial, failing to capture the underlying differences between the various forms of thought and experience, no other solutions have yet been proposed to represent these differences within the constraints of computational simulations.

2.1.3. Conclusions and Where the Model Falls in the Quadrants

A primary purpose of the CI model is to explain learning from text (e.g., rather than story comprehension). Thus, much of the research spurred by the model has centered on further understanding comprehension and memory for information expressed in expository texts (e.g., encyclopedia passages, textbooks) or in problem-solving tasks (e.g., algebra word problems, computer programming tasks). As such, much of the research has centered on the importance of prior knowledge and the effect of knowledge. This places the CI model primarily in quadrants C and D (i.e., more challenging, expository texts), though it has also successfully simulated a variety of experimental findings involving narrative text (Kintsch, 1998).

The CI model and its implementation is powerful and parsimonious, but it does not explain all of the processes described in the context of some models discussed later in this review (e.g., the role and implementation of reader goals), as well as additional processes that have been shown to support comprehension (e.g., metacognitive processes); nor does it address individual differences in reading comprehension ability (cf. Goldman, Varma, & Cote, 1996; McNamara & McDaniel, 2004). Moreover, we will see in the remaining models that the focus changes as the research centers more on understanding passages that depict relatively familiar scenarios, such as those found in narrative text. As such, the remaining six models tend to focus more on quadrants A and B (i.e., narrative and descriptive texts).

2.2. Structure-Building Model

2.2.1. Overview and Some Historical Context

Gernsbacher (1990, 1997) proposed the Structure-Building Model with the goal of providing a theory of comprehension regardless of medium. The processes and mechanisms included in the model are assumed to be general cognitive operations that function regardless of how the information is conveyed (e.g., text, discourse, picture, or video). Gernsbacher has contended that comprehension ability is not necessarily tied to modality specific, lower-level processes, but rather that there are general cognitive abilities involved in comprehension that are common across modalities (e.g., Gernsbacher et al., 1990). Thus, the focus of the modal was on identifying and describing the processes that operated during comprehension of various media such as texts and pictures.

2.2.2. Fundamental Assumptions

The Structure-Building model describes comprehension in terms of three primary processes: (a) *laying a foundation* for the mental representation of the text or discourse structure, (b) *mapping* information onto that foundation, and (c) *shifting* to new structures when new information cannot map onto the existing structure because it is incongruent or it is the beginning of a new idea. There are the two mechanisms that operate to determine the strength of memory nodes: *enhancement* increases activation and *suppression* decreases activation. The following describes the model's assumptions.

2.2.2.1. Laying the Foundation Laying the foundation refers to the processes that occur when a comprehender is first confronted with information (e.g., the beginning of a novel) or when the topic changes (e.g., the beginning of a chapter). According to the model, encoding the initial content in a discourse has an important status in the process of building the representation in that these structures essentially become a metaphorical foundation (functionally akin to the foundation of a building) for mapping subsequent information. Laying the foundation is assumed to be more resource demanding than other processes such as mapping. It is an iterative process that operates at the beginning of sections, story episodes, paragraphs, and even at the level of sentences.

The assumption that laying a foundation occurs during comprehension is supported by three sources of evidence. First, comprehenders show *slower reading times* during the initial stages of processing, such as when they read the first sentence of a paragraph (e.g., Glanzer, Fischer, & Dorfman, 1984; Graesser & Mandler, 1975) or the first sentence of an episode (e.g., Haberlandt, Berian, & Sandson, 1980). They also process more slowly the first picture of a picture story (Gernsbacher, 1983). Second, the first sentences in a story provide *better cues* for recalling the remainder of the story (Mandler & Goodman, 1982). And, finally, comprehenders show an advantage for *first mention*, where the first mentioned protagonist is more easily accessed than the second mentioned. For example, in the sentence, *Tina gathered the kindling, and Lisa set up the tent*, the first protagonist, Tina, is more quickly accessed in memory than is Lisa after reading both clauses (e.g., Gernsbacher, Hargreaves, & Beeman, 1989). Thus, even though Lisa is more recent, Tina is more accessible in memory.

2.2.2.2. Mapping and Shifting Once the foundation is laid, then the comprehender maps information onto the structure. The likelihood of information successfully *mapping* to the structure is driven by syntactic, referential, temporal, locational, and causal overlap (Gernsbacher & Givon, 1995). Overlap can be signaled in various ways including *syntactic* cues (Gernsbacher, 1991; Gernsbacher & Robertson, 2002), *concept repetition* (e.g., Haviland & Clark, 1974), *pronominal reference* (e.g., Lesgold, 1972), temporal and locational *contiguity* (Anderson, Garrod, & Sanford, 1983; Black, Turner, & Bower, 1979; Haenggi, Gernsbacher, & Bolliger, 1993), *causal coherence* (Deaton & Gernsbacher, 1997; Keenan, Baillet, & Brown, 1984; Myers et al., 1987; Zwaan, Magliano et al., 1995), and *emotional contiguity* (Gernsbacher, Goldsmith, & Robertson, 1992). When comprehenders cannot map to a structure, then a substructure is built, which in turn requires laying another foundation. This is called *shifting*. When a comprehender shifts, a new foundation or substructure is created, and the process is begun anew.

2.2.2.3. Enhancement and Suppression Comprehension depends on the efficient construction and maintenance of mental structures. If new information is related to the current structure, then it is *enhanced* and incorporated into the mental structure. It is added to the foundation. However, if new information is not related to the current structure, the comprehender may shift to a new mental substructure (building a new foundation), or alternatively, *suppress* the new irrelevant information.

Unlike most of the models discussed in this review, the Structure-Building model provides an explanation for *individual differences in comprehension skill*. According to the model, skilled and less-skilled comprehenders can be distinguished in terms of the efficiency of suppression processes which determine how quickly the irrelevant meanings of ambiguous words lose activation (Gernsbacher & Faust, 1991; Gernsbacher et al., 1990). Suppression is considered in the Structure-Building model to be the result of a *directed* reduction in activation by way of a mechanism that allows skilled comprehenders to inhibit irrelevant information, but is lacking for less-skilled comprehenders (e.g., Gernsbacher & St. John, 2000; cf. McNamara & McDaniel, 2004). For example, homographs such as bug, match, mold, and spade have multiple meanings that are initially activated regardless of the meanings' relevance to the sentence context (e.g., Kintsch & Mross, 1985; Swinney, 1979; cf. Simpson & Krueger, 1991). Gernsbacher et al. (1990) presented participants with experimental sentences ending with homographs such as *He dug with a spade* or control sentences such as *He dug with a shovel*, followed by an inappropriate target word, ACE. The participant decided if it was related to the previous sentence. They found an ambiguity effect such that response times to reject the inappropriate word were slower for the homograph sentences than for the control sentences when the target word was presented after only 50 ms. The slower response times indicated that the activation of the irrelevant meaning of the sentence-final ambiguous word competed with the correct response. However, after a 1000 ms delay, interference from the irrelevant meaning disappeared for skilled comprehenders, but remained for less-skilled comprehenders.

The efficiency of suppression also has implications for mapping and shifting. The model proposes that readers with more effective suppression mechanisms create fewer substructures because they are able to inhibit irrelevant information, rather than creating a new substructure. Less-skilled comprehenders, by contrast, are assumed to have inefficient suppression mechanisms, which leads to multiple substructures being created and maintained (Gernsbacher, 1990, 1997).

2.2.3. Conclusions and Where the Model Falls in the Quadrants

Like the Construction–Integration model, the Structure-Building model was intended to be a general model of comprehension. However, the Structure-Building model has focused primarily on narrative texts, and is supported primarily by experimental evidence using single sentences or pictures, and short, manipulated passages. Another unique aspect of the model is that there is greater focus on explaining individual differences in comprehension skill. Although reading ability differences are not conceptualized in terms of strategic comprehension in the Structure-Building model, the model might be considered to cover both quadrants A and B.

In principle, the metaphor of Structure Building should apply to reading situations that fall into quadrants C and D involving more challenging texts such as expository. However, the dimensions that support mapping specified by the model may not be adequate to explain the mapping processes for these texts. For example, building a coherent structure for a compare and contrast distinction may not be sufficiently supported by mapping between text constituents based on referential, causal, temporal, and spatial relationships.

Although Gernsbacher (1990, 1997) interprets the empirical findings used to support the notions of laying a foundation, shifting, and suppression as revealing separate and unique processes required in order to begin building a structure, or construct a mental representation, we take issue with this claim. In Section 5.1, we argue that these three mechanisms may be conceived of as properties that emerge from other dimensions of comprehension models. We contend that there are more parsimonious accounts and that a comprehensive model need not specify assumptions or parameters that are unique and distinct from those postulated for more basic comprehension and cognitive processes in order to account for processes associated with these three mechanisms.

2.3. The Resonance Model

2.3.1. Overview and Some Historical Context

The Resonance model was proposed by O'Brien, Myers, and colleagues (Albrecht & Myers, 1995; Albrecht & O'Brien, 1993; Myers & O'Brien, 1998; Myers, O'Brien, Albrecht, & Mason, 1994) to explain how information that is relatively distant from the focal sentence is reactivated. The primary focus was on activation of information from a text that is no longer available in working memory, though in principle the model also applies to the activation of relevant world knowledge as well (Rizzella & O'Brien, 2002). The reactivation and activation of knowledge is important to comprehension because this reactivated information is often critical for constructing coherence via the mapping process, the generation of inferences, and the construction of the textbase and situation models.

At the time that the model was initially proposed there was some debate regarding whether readers reactivate distal text information when there are local cohesive relationships such as those that arise from argument overlap (Graesser et al., 1994; McKoon & Ratcliff, 1992; Singer et al., 1994; Suh & Trabasso, 1993). The minimalist hypothesis proposed by McKoon and Ratcliff (1992) stated that in the absence of strategic, motivated, or goal-oriented processing of text, readers will not make inferences linking local and distant information. Rather, they will make inferences (e.g., to access distant text) only when there is a break in local coherence (i.e., the absence of explicit relationships between adjacent sentences) or when information from long-term memory is easily available. McKoon and Ratcliff contended that automatic inferences are made by readers only when neither explicit information nor general knowledge leads to a coherent representation of a text. Otherwise, if the text is locally coherent, inferences are assumed to be necessarily strategic.

Contrary to the minimalist hypothesis, the Resonance model proposed that knowledge activation and inference processes could be induced by breaks in either local or global coherence. They based their argument on evidence showing that distant information is reactivated by the reader, for example either to resolve anaphoric reference (e.g., Dell, McKoon, & Ratcliff, 1983; O'Brien, Duffy, & Myers, 1986) or to explain an action that deviates from expectations (e.g., Klin, 1994; Klin & Myers, 1993; Trabasso & Suh, 1993). It is important to note that although the Albrecht and O'Brien (1993) demonstrated that distal knowledge is reactivated even under conditions where there is local cohesion, the Resonance and Minimalist positions are no longer viewed as incompatible in that they both emphasize the role of bottom-up, memory-based processes in comprehension.

2.3.2. Fundamental Assumptions

Proponents of the Resonance model have argued that automatic, memory-based retrieval mechanisms (e.g., Hintzman, 1986; Ratcliff, 1978) were sufficient to explain inference processes. According to the *memory-based view*, the memory representation serves as a retrieval structure composed of images, perceptual features, conceptual features, and interitem information (e.g., Raaijmakers & Shiffrin, 1981). Elements in working memory serve as *cues*, or signals, to inactive portions of long-term memory. The Resonance model assumes that the activation is in continuous flux. Signals are constantly being sent, such that what *resonates* in long-term memory changes with each change to working memory contents. In addition, information from long-term memory resonates regardless of its relevance, akin to the *dumb activation* process proposed within the construction phase of Kintsch's (1988, 1998) CI model.

A prevalent paradigm used to support the model has been commonly called the *contradiction paradigm*. Participants read texts that describe characteristics of protagonists (e.g., vegetarian) or their goals (e.g., book a flight). In one version of the narratives, subsequent sentences contradict the earlier text information related to these characteristics or goals, and in the other version it does not. For example, Mary, the protagonist is described as a vegetarian. Later in the story, Mary orders a hamburger. In the consistent version of the story, information is provided that would explain why Mary would order a hamburger and in the inconsistent version that information is not provided. Increased reading times for the contradiction sentences in the inconsistent versions relative to the consistent versions are viewed as evidence that the contradiction is detected. Notably, most of reported effects in support of these claims show differences of less than 100 ms. Given that humans cannot engage in problem solving or strategic processes within 100 ms, this aspect of the data lends toward an interpretation of the effects of such coherence breaks as leading to automatic (resonance) rather than strategic processes to resolve the contradiction.

The fundamental assumption of the model is that concepts in working memory (e.g., from prior text) and in a focal sentence serve as signals to *both active and inactive elements* in the memory representation as well as the reader's knowledge base. Across several studies, it has been shown that at least three factors influence whether readers detect a contradiction in text: (a) *conceptual overlap* between trait or goal information and the target sentences, (b) *distance* between these two text regions, and (c) the extent to which the trait or goal information is *elaborated* in the text (e.g., Albrecht & Myers, 1995; Albrecht & O'Brien, 1993; Myers et al., 1994). These findings are interpreted as evidence that signals resonate as a function of these three factors.

One notable feature of the model is that there are no assumptions regarding the strength of elements: all inactive elements are assumed to have equal strength. More recent elements are more likely to resonate because they are assumed to have more features in common with the contents of working memory. However, the effect of feature overlap is also influenced by the degree to which the antecedents are elaborated in the distant discourse, wherein greater elaboration of a distant antecedent will make it more available than a recent, unelaborated antecedent (O'Brien, Plewes, & Albrecht, 1990). This occurs, again not because of the strength of the element, but because elaborated concepts have a greater *number of features* that can *resonate* to the contents of working memory. The presence of other potential antecedents also affects the Resonance process, such that more than one potential antecedent causes interference and slows processing (Corbett, 1984).

2.3.3. Conclusions and Where the Model Falls in the Quadrants

In sum, the Resonance model describes factors that influence the activation phase of comprehension (Long & Lea, 2005). It is compatible with the CI model, but centers more specifically on the factors that influence memory-based retrieval processes. In contrast to the CI model, the Resonance model has been tested solely with narrative texts, and thus the application of the model's assumptions to more challenging, expository texts has not been explored. Further, the model assumes that the Resonance process is automatic and therefore is not under the control of the reader, forgoing the need to assume active inference processes by the reader. Thus, little is said about the role of strategic comprehension processes, and researchers have yet to explore the role of comprehension skill in the context of this model (cf. Lassonde, O'Brien, & McNamara, 2008). As such, it seems to fall somewhere in the middle of quadrants A and B in that it does not describe a highly motivated or strategic reader (at the far edge of quadrant A), but also does not describe the minimalist reader (at the far edge of quadrant B).

2.4. The Event-Indexing Model

2.4.1. Overview and Some Historical Context

Since the introduction of the construct of *situation model* (van Dijk & Kintsch, 1983), it has dominated the focus of research in text comprehension (see Zwaan & Radvansky, 1998 for an extensive review). This focus has been driven, at least partially, by a lack of consensus among researchers regarding the representational nature of the construct and the processes that support its construction. A good deal of early research on situation models focused on assessing whether readers keep track of spatial relationships and the movements of characters within a narrative world (e.g., Glenberg, Meyer, & Lindem, 1987; Morrow, Bower, & Greenspan, 1989). However, later research indicated that spatiality is not a critical aspect of situation model construction. This research suggested that readers do not closely monitor and represent detailed spatial information during reading unless that information is important for establishing causal coherence (Sundermeier, van den Broek, & Zwaan, 2005), the reader has a goal to monitor spatial information (Zwaan & van Oostendorp, 1993), or the reader has considerable preexisting knowledge about the spatial layout of the fictive world (Morrow et al., 1989). Given the limited role of spatiality, combined with a lack of specificity offered by the CI model, the Event-Indexing model was developed with the purpose of more fully understanding the components and the processes involved in situation model construction (Magliano, Zwaan et al., 1999; Zwaan & Radvansky, 1998; Zwaan, Langston et al., 1995). It differs from the CI model in that it emphasizes the role of situation model construction in establishing relationships between discourse constituents, rather than knowledge-based inference generation. It also differs from the CI model in its focus on narrative, event-based texts. As such, much of the recent research on the situation model focuses on its role in establishing coherence in the reader's mental representation for narrative texts that include events.

2.4.2. Fundamental Assumptions

A central assumption of the Event-Indexing model is that the cognitive system is more attuned to perceive *dynamic events* (changes in states) rather than static information that is part of the larger event sequence. As such, it is most applicable to texts that describe events that unfold in space and time (e.g., narrative). Additionally, unlike the CI model, the Event-Indexing model emphasizes the role of verb semantics in conveying information about dynamic events (Zwaan, Langston et al., 1995). That is, verb predicates, rather than arguments (e.g., noun phrases; see Section 2.1.2.3), contain the majority of the semantic information regarding an event conveyed in a discourse. Similar to early proposals on situation models (Gernsbacher, 1990; Sanford & Garrod, 1981; van Dijk & Kintsch, 1983), the Event-Indexing model assumes that situational coherence can be established along multiple *dimensions of continuity*. However, the model goes beyond early theories of situation model construction and specifies that readers specifically monitor and establish coherence along five dimensions: *time, space, causality, motivation*, and *agents* (cf. Gernsbacher, 1990).

2.4.2.1. Stages of Mental Model Construction According to the Event-Indexing model, there are at least three stages of mental model construction. The first is the *current model*, which reflects the focal event reflected in the sentence that is being read. This representation contains the propositional representation and inferences that are generated during reading. Although these inferences can be knowledge-based in nature (e.g., Graesser, 1981; Graesser & Clark, 1985), the Event-Indexing model primarily focuses on the contribution of situational bridging inferences that are related to the five dimensions specified by the model. This distinguishes the Event-Indexing model from the CI model (Kintsch, 1988, 1998), which primarily focuses on how general and domain knowledge can be incorporated into the situation model.

Second, the *integrated model* refers to the situation model that is currently under construction and that is updated as the current model is computed and encoded into it. And, finally, the *complete model* reflects the model for a text as it is represented after reading has been completed. It is important to note that both the integrated and complete models are not static. The complete and integrated models are similar, but the complete model reflects the status of the representation when reading has been completed. When reading a novel over several sittings, the complete model would reflect the status of the representation at the end of each reading session. The activation levels and degrees of connectivity between story constituents change as each complete model is mapped onto the integrated model. The complete model can also change over time, and in particular as a function of ruminations and strategic processing that occur after reading a text.

2.4.2.2. Components of the Mental Representation Integrated and complete models can contain both static and dynamic elements (Copeland, Magliano, & Radvansky, 2006; Magliano et al., 2007; Zwaan & Radvansky, 1998). In terms of static components, a situation (or episode) is defined and bound by a *spatial–temporal framework*, which is the space and time where the event unfolds (e.g., doctor's office, between 2:00 and 3:00 in the afternoon). Time is static in this sense because there is only one time period used to provide the framework to define an event. Spatial–temporal frameworks contain *tokens* that represent entities, such as people, animals, objects, abstract concepts, and so forth. Associated with these entities can be various *properties*. These properties can include external physical characteristics, such as size, color, or weight, and internal properties, such as emotional states and goals. Finally, there are *structural relations* among entities within a framework, such as spatial, social, and ownership relations. Situation models contain dynamic elements in that events can be related to one another via *linking relations*, which correspond to the five dimensions specified by the model. These linking relationships can be conceptualized as situational bridging inferences and provide one basis for constructing coherence in understanding (Magliano, Zwaan et al., 1999; Zwaan, Magliano et al., 1995; Zwaan & Radvansky, 1998).

2.4.2.3. Continuity Monitoring The Event-Indexing model assumes that readers concurrently monitor and represent the extent to which text events are related along the dimensions of time, space, causality, intentionality, and agency (Magliano, Zwaan et al., 1999; Zwaan, Langston et al., 1995; Zwaan, Magliano et al., 1995; Zwaan & Radvansky, 1998). The current model can be mapped onto the integrated model to the extent that readers perceive and infer how the two models are related in terms of time, space, causality, motivation, and protagonist. As mentioned earlier, a fundamental difference between the Event-Indexing and CI models is that the Event-Indexing model assumes that mapping between discourse constituents is driven by event and causal relations between predicates (as conveyed by verb and verb phrases in particular) rather than argument overlap (Magliano, Zwaan et al., 1999; Zwaan, Langston et al., 1995; Zwaan, Magliano et al., 1995). This is based on the assumption and evidence that verbs are more informative of the event structure in a narrative than are nouns (Kurby, Britt, & Magliano, 2005; Radvansky, Zwaan, Federico, & Franklin, 1998; Zwaan, Langston et al., 1995).

When relationships between discourse constituents are readily perceived and inferred, establishing coherence can be achieved with little processing effort. However, as readers perceive breaks in continuity, their resolution may require effort and time (e.g., Magliano, Zwaan et al., 1999; Zwaan, Magliano et al., 1995). Moreover, breaks along several dimensions may indicate that a story episode has ended and a new one has begun (Magliano, Zwaan et al., 1999; Magliano et al., 2001; Zwaan & Radvansky, 1998). Studies in support of the Event-Indexing model have shown that readers monitor shifts in the dimensions specified by the model while processing a narrative (Magliano, Zwaan et al., 1999; Magliano et al., 2001; Rinck & Weber, 2003; Therriault & Rinck, 2007; Zwaan, Magliano et al., 1995). Many of these studies have relied on a correlational approach because it is difficult to construct experimental texts that contain manipulations of more than two dimensions. This approach involves conducting a discourse analysis of a text to determine how text constituents are related along all or a set of the five dimensions specified by the models. This discourse analysis is then correlated with behavioral measures, such as reading time or the likelihood of grouping story events together.

In general, the assumption that readers monitor continuity of events along the dimensions specified by the model has been substantiated, but not all dimensions carry equal weight. For example, Magliano, Miller, and Zwaan (2001) found that when processing narrative film, breaks in temporal cohesion had a bigger impact on the perception of the event structure than breaks in spatial cohesion, despite the fact that film is an inherently spatial medium. Similarly, during the first reading of a text, reading times increase when there are breaks in causal and temporal cohesion, but not spatial cohesion (Magliano, Zwaan et al., 1999; Zwaan, Magliano et al., 1995). Nonetheless, readers do appear to monitor breaks in spatial cohesion when rereading a text (Zwaan, Magliano et al., 1995).

2.4.3. Conclusions and Where the Model Falls in the Quadrants

In sum, the Event-Indexing model specifies processes that are primarily involved in establishing relationships between discourse constituents, rather than the generation of knowledge-based inferences (i.e., incorporating general or episodic knowledge into the discourse representation). Because the inferences are necessarily based on general world knowledge, such as knowing a likely sequence of events, we view the process of establishing these relationships as inferential in nature and conceptualize the mapping processes specified by the Event-Indexing within the general class of bridging inferences (i.e., inferences that establish coherence between propositions in the textbase).

The Event-Indexing model is applicable exclusively to texts that describe event sequences. As such, it is most relevant to research on narrative comprehension, including both simple narratives (Magliano, Zwaan et al., 1999) and more challenging literary narratives (Zwaan, Magliano et al., 1995). However, it has not been tested in the context of expository or argumentative texts, and likely would not apply as well or consistently to those genres. The model also makes no assumptions regarding reading ability or reading goals, though one would assume that the reader must be sufficiently motivated and skilled to generate the inferences necessary to construct a coherent situation model. As such, the event-based model seems to apply more to reading contexts that fall within quadrant A where processing should be relatively easy and the reader sufficiently skilled.

2.5. The Causal Network Model

2.5.1. Overview and Historical Context

As noted in the previous section, there was a general drive among text and discourse researchers to better understand the nature of the situation model. One notable line of research in that regard was pursued by Trabasso and colleagues, who focused on the role of causality in comprehension (Suh & Trabasso, 1993; Trabasso & Sperry, 1985; Trabasso & van den Broek, 1985; Trabasso et al., 1989; van den Broek & Trabasso, 1986). The Causal Network model (Trabasso et al., 1989) made two critical contributions. First, it provided a psychological account of how readers generate causal inferences and build representations for the causal episodes described in a narrative text. Second, it provided a principled system of discourse analysis for theoretically identifying the potential causal relationships between story clauses. This system offers discourse researchers a tool to identify structural features of a text, which can then form the basis to generate principled predictions regarding causal processing (Magliano & Graesser, 1991). Conducting such a discourse analysis certainly requires training. However, participants who are naïve to formal definitions of necessity make causal relatedness judgments that are sensitive to whether there are necessary relationships between two events (Trabasso et al., 1989), which lends credence to the psychological validity of the criteria for determining causal relationships between events.

2.5.2. Fundamental Assumptions

The Causal Network model provides a theoretical account of some aspects of inference generation and situation model construction during reading. An important assumption of this model is that understanding is primarily achieved through *causal reasoning*. That is, causal inferences provide the primary basis for constructing a coherent representation for a text, at least for texts that describe events that unfold over time and place. Accordingly, there exists within the text an "ideal" causal structure that reflects the implicit causal relationships between discourse clauses, and this structure can be uncovered through principled decision rules that drive the discourse analysis.

2.5.2.1. Components of the Mental Representation The analytic model is based on a *general transition network* that specifies conceptual categories of the narrative constituents that occur in an event-based text and the types of causal relationships that bind these constituents. Story clauses can be classified according to how they fit into an episodic structure, which consists of categories of story units (Stein & Glenn, 1979). These categories include *settings, events, goals, attempts, outcomes*, and *reactions*. Settings of story episodes introduce characters, time, and place. Events are unintentional changes in state, and can be distinguished from outcomes, which are changes in state that are the direct result of intentional actions. Goals reflect the desired states of agents depicted in stories. Attempts are the actions of agents, presumably to achieve some stated or unstated goal. Finally, reactions are changes of psychological states of agents (e.g., affective responses, changes in knowledge states).

Although the model bears some resemblance to story grammar theories (Mandler & Johnson, 1977; Stein & Glenn, 1979; Thorndyke, 1977), the primary difference between these theories and the general transition network is the specification of the types of causal relationships that are constrained by the conceptual categories. The model assumes that there are four types of causal relationships: *enabling, psychological, motivational*, and *physical*. The causal relationships between story clauses are relationships constrained by the story categories. Settings enable all other categories. Events can physically cause other events and psychologically cause characters to have goals and reactions. Goals can motivate other goals, attempts, and outcomes. Attempts can enable other attempts and physically cause or enable outcomes. Outcomes can enable or physically cause other outcomes. Outcomes, as well as events, can psychologically cause characters to have reactions and goals.

2.5.2.2. Discourse Analysis The model specifies a discourse analysis for identifying the potential causal relationships afforded by the text. The causal relationships specified by the model for a particular story are based on the logical criteria of *necessity* and *weak sufficiency* in the circumstances (Mackie, 1980). An event A is necessary for an event B if event B will not occur in the story without event A. Furthermore, if event A occurs in the story, then event B is likely to follow. Conducting a Causal Network analysis yields a network of causal relationships, such that some story constituents are more central than others (Trabasso & van den Broek, 1985; Trabasso et al., 1989). This network can take on a hierarchical structure, especially when there is an implicit hierarchy of goals (Suh & Trabasso, 1993; Trabasso & Suh, 1993). A Causal Network analysis can then be used to predict a variety of comprehension outcomes, such as inference generation (Magliano, Trabasso et al., 1999; Trabasso & Suh, 1993; van den Broek, 1990), the availability of goals (Lutz & Radvansky, 1997; Magliano & Radvansky, 2001; Suh & Trabasso, 1993), perceived strength of causal relationships between story constituents (Trabasso et al., 1989), sentence importance judgments (Trabasso & Sperry, 1985), and the likelihood of recalling story events (Trabasso & van den Broek, 1985; van den Broek & Trabasso, 1986).

2.5.2.3. Implementation of the Model A version of the Causal Network model was implemented in the context of a hybrid-connectionist model derived from the CI model (Langston & Trabasso, 1999; Langston, Trabasso, & Magliano, 1999). The Causal Network model has one main storage buffer called the text representation, which contains nodes, connections between nodes, and quantitative values that change over time as each new node is entered. The quantitative values correspond to the activation values and connection strengths of each node. The model executes computations based on a spread of activation among nodes in the model, which leads to an adjustment of connection strengths.

The formulas that govern the spread of activation and settling of the network are nearly identical to the CI model. However, there are several important differences between the CI model and the implementation of the Causal Network model. First, the CI model derives the network representation from hand-coded propositions. In contrast, the Causal Network model network is derived from a Causal Network analysis and includes a series of causal relationships between nodes representing story clauses. This input does not take into account the episodic category of the clauses, type of causal relationships, or the direction of the causes (A causes B or B causes A). Another difference is that the implementation of the Causal Network model is designed to model only the effects of establishing causal relationships on processing and the ensuing memorial representation. On the other hand, the CI model generally includes knowledge that is not explicit in the text.

A final difference is that the implementation of the Causal Network model does not incorporate a working memory constraint. That is, all nodes currently represented in the network can be activated, not simply those that are within parameters of the WM constraints determined by the researcher. The model assumes that the activation of all nodes can dynamically change as a function of introducing new causal relationships. This assumption has some psychological plausibility if one assumes that there is a long-term working memory that renders some concepts quickly accessible (Ericsson & Kintsch, 1995). The removal of working memory constraints is also more plausible if it is assumed that some concepts receive activation, but are not consciously available to the reader.

The model yields three measures (i.e., node activation values, cycles to settle, and node connection strengths) that have been used to simulate behavioral data from experiments conducted by Trabasso and his colleagues and other researchers (Langston & Trabasso, 1999; Langston et al., 1999). These measures can be used to simulate a variety of online and offline measures of processing and comprehension. For example, Trabasso and Suh (1993; Suh & Trabasso, 1993) assessed the availability of character goal information as a function of whether there was an implicit hierarchical causal structure or linear causal structure to the text. Both think-aloud and probe recognition latencies demonstrated that the character goals have a higher state of activation at critical target sentences (that have implicit causal relations to the explicit goal statements) in the hierarchical text than the linear text. Activation levels produced by the model have strong correlations with these behavioral measures (Langston et al., 1999). As another example, the model was used to simulate a well-established finding that reading times decrease for target sentences as a function of the distance between the causal relationship and the prior context (Myers, Shinjo, & Duffy, 1987). Langston and Trabasso (1999) constructed a causal network for the materials used by Myers et al. (1987) and used connection strengths to simulate causal distance. They found significant negative correlations between connection strengths and reading time.

2.5.3. Conclusions and Where the Model Falls in the Quadrants

The research conducted in support of the Causal Network model demonstrates the importance of causality for comprehension and memory of text. In fact, one could argue that is a central dimension of situation models for event-based text. Importantly, the Causal Network model can be implemented in a connectionist framework, which illustrates that the Causal Network model is fundamentally compatible with the CI model. In contrast, however, research to support the Causal Network model, like the Event-Indexing model, has lent greater credence to the importance of the other situational relationships (e.g., causal, temporal, spatial) besides the referential connections that dominate the CI model.

Like the Event-Indexing model, the Causal Network model is exclusively applicable to texts that describe events. In principle, event-based texts and texts with apparent causal relationships can occur in any of the reading situations depicted in the four quadrants. However, the model is limited to specifying causal inferences that are based on explicit content in the discourse context and cannot specify causal inferences that are based on general knowledge.

Although the Causal Network model has been aligned with perspectives of comprehension that assume that comprehension arises from effortful processing (Graesser et al., 1994; Magliano & Radvansky, 2001), the model is agnostic as to whether the connections are established via bottom-up or effortful processing. That is, it does not make specific assumptions regarding the roles of strategic processing in establishing causal relationships (cf. Magliano & Radvansky, 2001). Nonetheless, as with the Event-Indexing model, we can assume that the reader must be sufficiently motivated and skilled to encode causal relationships in text and generate causal inferences, placing the Causal Network model more within quadrant A.

2.6. The Constructionist Theory

2.6.1. Overview and Historical Context

The Constructionist theory of comprehension (Graesser et al., 1994) was specifically proposed to explain those factors that constrain the inference processes that support comprehension during reading. At the time that Graesser et al.'s paper was published, a central research question in discourse psychology regarded what inferences were routinely generated during reading (e.g., Long & Golding, 1993; Magliano, Baggett, Johnson, & Graesser, 1993; McKoon & Ratcliff, 1992; Potts, Keenan, & Golding, 1988). For example, as discussed earlier, the minimalist hypothesis assumed that inferences that serve to establish global coherence are generated when they are supported by automatic memory retrieval or when local coherence cannot be achieved. Additionally, McKoon and Ratcliff (1992) characterized Constructionist theories of comprehension as assuming that readers routinely generate all possible inferences. The Constructionist theory was in part proposed in response to this claim. Specifically, it conveys a constructivist notion of inference generation that is constrained and makes specific predictions regarding the types of inferences that are routinely generated during reading and the conditions that give rise to their generation.

Since the publication of this seminal paper, a more central issue in discourse comprehension research has been the assessment of the extent to which comprehension is supported by bottom-up, data-driven processes as compared to top-down, explanatory processes (Albrecht & Myers, 1995; Magliano & Radvansky, 2001; Myers & O'Brien, 1998). Although the Constructionist theory acknowledges that comprehension is supported by memory-based retrieval and automatic processes (Graesser et al., 1994), the theory clearly emphasizes the role of top-down and controlled processes in comprehension. Likewise, those researchers who emphasize the role of bottom-up processes clearly acknowledge that comprehension can be supported by top-down processing (McKoon & Ratcliff, 1992, 1998; Myers & O'Brien, 1998). Despite this mutual acknowledgment of the role of top-down and bottom-up processes in comprehension, many researchers who have advocated bottom-up perspectives took umbrage with the Constructionist theory (e.g., Albrecht & Myers, 1995).

2.6.2. Fundamental Assumptions

According to the Constructionist theory, deep understanding is achieved through active, constructive processes that have been characterized as *search for meaning* (Bartlett, 1932; Graesser et al., 1994; Stein & Trabasso, 1985). There are three assumptions of the theory that define a search for meaning. A *coherence assumption* specifies that deep meaning is achieved when readers construct situation models that reflect both local and global coherence. An *explanation assumption* specifies that individuals have a drive to seek explanations for events that they experience (Hart & Honore, 1959; Hilton & Slugowski, 1986; Mackie, 1980; Ranney & Thagard, 1988; Schank, 1986). Explanations provide one basis for achieving coherence in understanding (Graesser et al., 1994; Magliano, Trabasso et al., 1999). The model assumes that readers routinely assess the extent to which they can generate explanations for events based on knowledge available to them, particularly regarding causal antecedents, agent goals, and causal relationships. To this end, readers engage in an evaluative process that consists of a naïve assessment of whether inferred and implicit antecedents provide the necessary and sufficient conditions for the focal event (Mackie, 1980; Trabasso et al., 1989).

Finally, a *reader goal assumption* specifies that readers construct representations that are consistent with their comprehension goals. If the goal entails a standard of comprehension consistent with meaning making, then readers will generate inferences that support the construction of a coherent situation model (i.e., local and globally coherent). Contrastingly, if a goal involves shallow processing (e.g., skimming through a text for key words), then the resulting text representation will be disjointed and incoherent.

The theory is formally described as a set of production rules that specify the discourse features that must be present in a focal sentence for the cognitive processes that give rise to these inferences to occur. For example, one production rule states that if the current discourse constituent states the action or goal of a character, the readers will explain why these actions or goals occurred. Readers will "search" information sources in working memory or long-term memory for plausible superordinate goals. However, to our knowledge these production rules have never been formally implemented.

The theory makes specific predictions regarding the types of knowledge-based inferences that should be routinely generated during reading, at least when the readers' goal is to deeply comprehend what they are reading.

The theory in general predicts that readers generate inferences that provide a basis for achieving explanatory coherence. Consistent with the model, there is a vast amount of evidence that causal antecedent inferences (Magliano et al., 1993; Singer & Halldorson, 1996; Zwaan, Magliano et al., 1995) and character goal inferences (Long & Golding, 1993; Singer & Richards, 2005; Suh & Trabasso, 1993) are routinely generated during reading, which are the primary inferences that provide a basis for achieving explanatory coherence. In contrast, elaborative and predictive inferences, which are not central for achieving explanatory coherences, are not routinely generated during reading (e.g., Magliano et al., 1993) or are only generated when they are highly constrained by the discourse context (e.g., Fincher-Kiefer, 1993; Murray, Klin, & Myers, 1993; van den Broek, 1990; Whitney, Ritchie, & Crane, 1992).

As mentioned earlier, researchers who advocated bottom-up perspective of comprehension took issue with the Construction theory. Long and Lea (2005) clarified at least one reason why these researchers had issues with the Constructionist theory. Specifically, Graesser et al.'s (1994, Table 2) articulation of the production rules that guide inference processing suggests that prior knowledge is actively searched to meet the drive for explanatory coherence. Long and Lea (2005) provide a detailed discussion of why an active search is not psychologically plausible. They conceptualized the search for meaning as an evaluative process that operates on information that has become available to working memory via memory-based retrieval, which is consistent with the Resonance model (Myers & O'Brien, 1998).

2.6.3. Conclusions and Where the Model Falls in the Quadrants

The Constructionist theory specifies inference and evaluative processes that support comprehension. The model can be aptly thought of as describing a highly motivated, strategic reader who routinely engages in goal-directed, effortful processing during comprehension, placing the model in quadrants A and C. However, one could venture that by specifying the processes expected in ideal reading situations, the model consequently describes what the less strategic or less-skilled reader does *not* do (Bereiter & Bird, 1985; McNamara, 2007; McNamara et al., 2006; O'Reilly & McNamara, 2007a; Paris & Myers, 1978; Pressley & Afflerbach, 1995). If the model is conceived as also describing what happens (i.e., comprehension deficits) when the three reader assumptions (i.e., coherence, explanation, goals) fail, then the model might be said to describe comprehension across all four quadrants. However, there is little specification in the model as to how comprehension will vary as a function of the reader's adherence to these assumptions. Nor does the model specify whether or how comprehension will vary as a function of the difficulty or characteristics of the text. Nonetheless, of the models discussed thus far, along with the CI model, we see the Constructionist model as most applicable to the study of comprehension in authentic educational settings. It is these contexts where researchers strive to understand the factors that influence readers' drive for the search for meaning and to identify ways to help struggling readers learn how to read strategically (Graesser, 2007; McNamara, 2007).

2.7. The Landscape Model

2.7.1. Overview

The Landscape model, developed by van den Broek and colleagues, is designed to simulate the fluctuation of concept activation while reading (Linderholm et al., 2004; Tzeng et al., 2005; van den Broek et al., 1999, 2005). The model is similar to the CI model (Kintsch, 1998) in a number of ways. First, it is an implemented model and consequently subsumes the assumptions listed in Table 1. In addition, similar to the CI model, it assumes that there are four sources of activation, including the current input, carryover from the prior cycle, reinstatements from prior information sources, and related knowledge. Also like the CI model, the reading process can be viewed in a cyclical manner across the course of reading and parameters can be modified to test a variety of theories.

Because of its computational similarity to the CI model, it is useful to compare the two. The primary difference between the Landscape model and the Construction–Integration model regards assumptions on activation and learning. Specifically, according to the Landscape model, the activation of concepts can be automatic or strategic through assumptions regarding the source of activation and the amount of activation.

2.7.2. Fundamental Assumptions

The Landscape model proposes that there are two types of mechanisms are involved in reinstatements and prior knowledge activations: *cohort activation* and *coherence-based retrieval*.

2.7.2.1. Cohort Activation Cohort activation varies from 0 to 1 and essentially serves the function of passively mapping related concepts to the reader's mental representation of the text. When a concept is activated during reading, all other concepts concurrently activated become associated with it via a delta learning rule (Gluck & Bower, 1988a,b; McClelland & Rumelhart, 1985). This rule results in an asymptotic learning curve as a function of the number of times concepts co-occur in working memory. Via this process, each concept connects with other concepts to form a *cohort*, which are associative memory traces or textual interconnections. When a concept in a cohort is activated, the other concepts in that cohort are also activated, assuming limited working memory resources. This mechanism can be used to simulate memory-based inferences as described by the Resonance model (Myers & O'Brien, 1998; O'Brien & Myers, 1999;

O'Brien, Rizzella, Albrecht, & Halleran, 1998; van den Broek et al., 2005). However, the Resonance model does not assume learning per se, and the Landscape model also includes a learning rate parameter, which determines the amount of learning as a function of another parameter called *expectancy*.

2.7.2.2. Coherence-Based Retrieval Coherence-based retrieval is a strategic mechanism that takes into account the reader's standards of coherence, for example as influenced by reading goals (Linderholm et al., 2004; van den Broek et al., 2005). It does so through a parameter that varies the degree of activation of text elements. Depending on the standard of coherence assumed to be adopted by the reader, the experimenter sets this parameter to a value between 1 and 5 as a function of the element's importance to certain relations in the text (e.g., referential, causal, temporal, and spatial connections). As such, coherence-based retrieval is intended to simulate the *search/effort after meaning* mechanism described by the Constructionist view of reading (Graesser et al., 1994; Singer et al., 1994). For example, simulating a more superficial reading goal involves lowering the activation values for elements assumed to be involved in causal relations. Contrary to the Constructionist view, the Landscape model seems to assume search after meaning processes are reflective of either retrieval mechanisms or late reading processes. Specifically, when van den Broek et al. (2005) conducted a simulation to account for both Resonance and Constructionist processes, they assumed that these two types of processes varied along a time line of early (bottom-up) and late (top-down) processes, respectively. Notably, the assumption that Constructionist processes are late (after 500 ms) and top-down runs somewhat counter to the original claims by Graesser et al. (1994), but is in line with a good deal of experimental evidence (Long & Golding, 1993; Magliano et al., 1993; Till, Mross, & Kintsch, 1988).

2.7.2.3. Other Differences Compared to CI Model The Landscape model differs from the CI model in two other ways. First, there are no assumptions in the Landscape model concerning levels of comprehension. That is, whereas the CI model assumes that there are surface, textbase, and situation model levels of understanding, the Landscape model does not implement these differences.

Second, units of analysis in the Landscape model can be the proposition, idea unit, sentence, or essentially whatever is of interest to the experimenter. In contrast, the notion of the proposition as the unit of analysis in the CI model is inherent to its theoretical basis. This aspect of the Landscape model moves it away from notion of the proposition as the fundamental unit of processing. Notably, one consequence of this is that the model tends to put a more weight on each word in the text. Further, although the move away from the proposition facilitates implementation for some aspects of the model (i.e., one need not propositionalize the text), it also renders more difficult comparisons between various uses of the model.

2.7.2.4. *Empirical Evidence*

The Landscape model is motivated by a good deal of experimental evidence and has been validated in several studies. One way to validate the model is to examine the correlations between participants' recall of a text and the activation values for the concepts in that text. If activation values are high, then the participant should be highly likely to recall those concepts (e.g., van den Broek, Virtue, Everson, Tzeng, & Sung, 2002) and reading times should be more rapid (Linderholm et al., 2004), at least for narrative text. In one such study by van den Broek, Risden, and Husebye-Hartmann (1995), seven participants read narrative passages and after each sentence, they rated a list of concepts on their relatedness. Their ratings correlated 0.79 with the model's activation values, but only 0.46 when referential and causal reinstatements were removed from the model. These same participants also recalled the passages after a delay. Including both node and link strengths, the model accounted for 64% of the variance. Additionally, the most highly activated concept across the cycles was highly likely to be recalled first.

2.7.3. Conclusions and Where the Model Falls in the Quadrants

One strength of the Landscape model is its flexibility. However, this is also its greatest weakness. To use the implemented model, the text must be parsed (without set guidelines) and all of the elements' activation values and connections (i.e., the activation matrix) must be set by hand. This freedom can lead to both human error and an ability to change a multitude of parameters and settings to fit the data. Also, because the values must be set by hand, the model is effectively limited to texts with a relatively small number of sentences.

Nonetheless, the Landscape model provides the first move toward a model that unites assumptions from competing models, including the Construction–Integration model, the Resonance model, and the Constructionist model. Moreover, although it has been primarily tested in the context of narrative texts, it is the most comprehensive of the models in that comes closest to covering all four quadrants and places a good deal of focus on simulating individual differences.

3. Evaluation of Models

3.1. Dimensions That Vary Across Models

In the prior section, we described seven influential models of discourse comprehension. Our central assumption is that by and large, these models are not mutually exclusive, but rather focus on different aspects of comprehension. One way to conceptualize these differences is in terms of the specific dimensions assumed by each model. We have already described eight dimensions that are relatively common across the models (Table 1). We also identified 29 dimensions that varied sufficiently among the models to afford comparisons between them. Certainly there other dimensions that we could have considered; however, these 29 seemed to capture the most important aspects of these models.

We grouped these dimensions into four categories: *features* of the discourse, *processes* (i.e., both continuous and late), *products*, and *extratextual dimensions*. As shown in Table 2, we rated each of the seven models on the relative importance within the model of the 29 dimensions. The labels are somewhat arbitrary, but in our ranking a "3" indicates that the dimension was deemed to be central to the model, which means that the model postulates detailed assumptions regarding this dimension and it is a dimension that distinguishes that model or type of model from others. A "2" indicates that the dimension is deemed to be important to the model but does not specify detailed assumptions regarding the dimension. A "1" indicates that the authors have acknowledged the importance of the dimension in general, but it is beyond the scope of the model. A "0" indicates that the dimension is omitted by the model. Finally, a "−1" indicates that the dimension is contradictory to the model.

These ratings are not experimental data by any means but rather provide an overview of our own extensive analysis of these models. And, the ratings naturally reflect our own biases and personal understandings of the models. In sum, the ratings are debatable (and we debated quite a bit about them). Nonetheless, they provide a useful platform to compare the models' assumptions.

In the following sections, we describe these dimensions and discuss the relative centrality of each dimension across the seven models. We approach this task by examining the ratings within each of the four categories of dimensions.

3.1.1. Features of the Discourse

The four dimensions that we categorized as features are listed and defined in Table 3. Features of the discourse refer to aspects of the discourse content that occur either within text constituents or across text constituents. These features are important because they provide input or cues to the cognitive systems that support comprehension for processing (Gernsbacher & Givon, 1995; Graesser et al., 2004; Magliano & Schleich, 2000). There are innumerable features of discourse ranging across the characteristics of the word, the sentence, the discourse context, and so on. But, here, we have listed only four features that we believe distinguish between the seven models.

Each model assumes that at least one feature of the discourse is central because these features are the basis for mapping processes. Some theories

Table 2 Ratings of the Seven Models on Model Dimensions as to Whether the Dimension is Critical (3), Important (2), Acknowledged (1), Absent (0), or Contradictory (− 1).

		Model						
Category	Dimension	Construction–integration	Structure building	Resonance	Constructionist	Event indexing	Causal network	Landscape
Features	Grammatical morphology and syntax	1	2	0	0	1	0	0
	Referential cohesion	3	3	3	1	− 1	− 1	2
	Situational semantics	2	0	0	1	2	0	0
	Situational cohesion	1	2	0	3	3	3	3
Processes	Dynamic activation	2	2	3	1	0	3	3
	Integration/settling	3	0	1	1	0	2	1
	Memory-based retrieval	2	0	3	1	1	0	2
	Knowledge-based inferencing	3	1	2	3	1	0	2
	Dumb activation	3	2	3	0	0	0	2
	Continuity monitoring	1	0	1	3	3	3	1
	Laying a foundation	0	3	0	0	0	0	0
	Shifting	0	3	0	0	3	0	0
	Suppression	2	3	1	0	0	0	1
Products	Situation model	3	1	0	2	3	2	2
	Propositional textbase	3	1	0	1	1	0	1
	Levels of representation	3	0	0	1	1	0	0

(*Continued*)

Table 2 (*Continued*)

Category	Dimension	Model						
		Construction–integration	Structure building	Resonance	Constructionist	Event indexing	Causal network	Landscape
	Local coherence	3	0	2	3	0	1	1
	Global coherence	3	0	2	3	0	1	1
	Sources of information	2	0	1	1	0	0	3
	Levels of comprehension	3	1	0	2	0	0	1
	Hierarchically structured representation	3	1	0	2	0	3	1
Extratextual	Goals	1	0	0	3	0	0	2
	Task	0	0	0	1	0	0	0
	Affect	1	0	0	0	0	0	0
	Standards of coherence	0	0	0	3	0	0	3
	Evaluation of comprehension	1	0	0	3	0	0	2
	Drive for explanation	0	0	−1	3	0	3	1
	Embodiment	1	0	0	0	0	0	0
	Imagery	1	1	0	0	1	0	0

Table 3 Definitions for Features that Vary in Importance Across the Seven Comprehension Models.

Grammatical morphology and syntax. Surface form and grammatical morphemes provide cues regarding the construction of the mental representation for a discourse. For example verb aspect provides readers with cues regarding whether events continue in the narrative context (e.g., walked to the store is completed, walking to the store is ongoing), which has implications on the availability of verb information and other constituents in working memory.
Referential cohesion. Referential cohesion refers to the amount of explicit overlap between referents, concepts, and ideas in a text. There is greater referential cohesion to the extent that words, nouns, concepts, and ideas overlap between sentences and between paragraphs. Local referential cohesion refers to properties of the text between consecutive sentences and near sentences. Global cohesion refers to how each sentence and paragraph overlaps with the text as a whole.
Situational semantics. Situational semantics comprise information within a discourse constituent (e.g., clause, sentence) that describes circumstance such as place, time, or manner. In a propositional representation, this information may constitute subpropositions for a core proposition. For example, She had dinner at midnight, is comprised of the core proposition, had(she, dinner) and the subproposition, time(midnight).
Situational cohesion. Situational cohesion is reflected by the potential for deriving connections between propositions based on situational semantics and implicit relationships. Discourse constituents can be related to one another along several dimensions of situational continuity: time, space, causality, goals, and entities. The Causal Network model is an example of a tool to establish the presence of cues related to situational cohesion.

emphasize the importance of referential cohesion (e.g., the CI model), whereas others emphasize the role of situational cohesion (e.g., the Event-Indexing model). Referential cohesion refers to the extent to which arguments in the current discourse input explicitly connect to arguments or concepts that have been established in the prior discourse. The CI model, for example, determines links between concepts in adjacent propositions according to the overlap between referents or arguments. Referential cohesion thus provides one potential source of information to guide the process of mapping. Referential cohesion is either central or important to the CI, Structure-Building, Resonance, and Landscape models, whereas it can be considered contradictory to the Event-Indexing and Causal Network models. In lieu of referential cohesion, the latter two models determine links via connections related to actions and events as conveyed in predicates.

As we discussed in Section 2, the difference between these models centers around the emphasis on arguments versus predicates in the mapping process. The Event-Indexing model assumes that verbs guide the mapping process because they carry the bulk of the information about the events in a text (Zwaan, Langston et al., 1995). There is some controversy with respect to whether referential cohesion is sufficient to guide the mapping process (Giora, 1985; Kintsch, 1995; Magliano, Zwaan et al., 1999; Trabasso, Suh, & Payton, 1995; Zwaan, Langston et al., 1995). Although Kintsch (1995) acknowledges that situational cohesion may influence the mapping process, he has argued this dimension should be highly correlated with referential cohesion. However, there is some evidence that this is not the case with naturalistic narrative text and that, at least for narrative texts, situational cohesion is central to mapping (Zwaan, Magliano et al., 1995).

Indeed, much of the controversy over the differential focus on these two features is likely driven by the foci of the models on different genres of texts. Narrative texts likely require different processes from the reader than do expository texts. Indeed, there a many differences between narrative and expository texts. Narrative texts are more easily and successfully understood than expository texts (Best, Ozuru, Floyd, & McNamara, 2006). Narrative texts are read nearly twice as fast as expository text (Graesser, Hauft-Smith, Cohen, & Pyles, 1980; Haberlandt & Graesser, 1985), but recalled nearly twice as well (Graesser, Hoffman, & Clark, 1980). Narrative texts are more likely to convey life experiences, person-oriented dialogue, and familiar language in the oral tradition than are expository texts (Bruner, 1986; Rubin, 1995; Tonjes, Wolpow, & Zintz, 1999). In contrast, the purpose of expository texts is to inform the reader of new information, so by definition they generally use more unfamiliar words and demand more knowledge that fewer people possess. As such we assume that both referential and situational cohesion should be important for a comprehensive model of comprehension, but that the relative importance of these forms of cohesion in the mapping process may vary from discourse to discourse.

There were two dimensions of features that were not deemed to be important across models, situational semantics and grammatical morphology and syntax. Situational semantics refers to the semantic content that is derived from the construction of a propositional representation of a text. This may lead one to assume that researchers proposing these theories assume that these features are unimportant, but this is likely not the case. Many theories, such as the CI model operate on the assumption that the propositions have already been constructed. Therefore, they typically do not explicitly describe how situational semantics are derived, what kinds of information are represented, and how they guide processing. This also explains why morphology and syntax are left out as well. That is, this lower-level information is typically lost after propositions are constructed (Fletcher & Chrysler, 1990; Schmalhofer & Glavanov, 1986). However, there is some evidence that this could be a mistake because there is evidence that these features influence the availability of information in working memory and guide processes such as mapping and situation model construction (Gernsbacher & Jescheniak, 1995; Gernsbacher & Shroyer, 1989; Givon, 1989, 1992, 1995; Magliano & Schleich, 2000; Morrow, 1985, 1986). Although a few models acknowledge the importance of lower-level features, they do not make specific assumptions regarding how morphology and syntax guide processing.

3.1.2. Comprehension Processes

Obviously, the primary input during reading is the text and therefore, the processes assumed by the models operate on the features of the discourse. Virtually all of the models we discuss here are processing models and therefore, the critical assumptions posited in the theories focus on processing. Also, the primary differences between the models are reflected in the relative importance of comprehension processes. The processes we have listed in Tables 2 and 4 vary from continuous processes that operate throughout the processing of a text constituent (e.g., clause or sentence) and late processes, which may operate near the end of processing a text constituent and may involve spill over processing. Continuous processes begin immediately upon the activation of information that supports them (Just & Carpenter, 1980). We do not include early processes in this list because the vast majority of these refer to lower-level processes (e.g., decoding, syntactic) that are not within the scope of these theories.

With two exceptions (i.e., the Constructionist and Event-Indexing models), the notion that activation of information sources dynamically fluctuates across processing cycles is relatively central to most theories. Although dynamic activation would presumably be tied to the integration of concepts and the network settling toward a stable mental representation, this latter process is explicit within only four of the models, namely the CI, Resonance, Causal Network models, and Landscape Model. The dynamic fluctuation of activation in the mental representation can be mediated by passive, memory-based retrieval mechanisms (Myers & O'Brien, 1998) or as a result of establishing relationships between discourse constituents (Langston & Trabasso, 1999; Langston et al., 1999).

However, one general observation that distinguishes the seven models is the relative emphasis on the importance of automatic, bottom-up processes and goal directed, top-down processes in support of comprehension. For example, the CI and Resonance models place a heavy emphasis on the role of automatic, bottom-up processes in supporting mapping. Neither deny that top-down processes operate, but assume that much of the work that supports mapping is achieved through an automatic, integration/settling process. In contrast, the Constructionist model specifies the role of goal directed processing on comprehension. Although the Constructionist and

Table 4 Definitions for Processes that Vary in Importance Across the Seven Comprehension Models.

Dynamic activation. The availability of information sources in working memory and long-term working memory are in constant flux and change when new relationships are established. As such, activation dynamically changes across the time span of information processing.

Integration/settling. Information from various sources is integrated using an iterative process until the network shows little change in values between iterations. The network settles when there is little change in activation values and it has become stable.

Memory-based retrieval. Information from the text representation or prior knowledge is probabilistically retrieved based on principles related to memory and features of the text including referential cohesion, elaboration of the antecedent, availability of other antecedents, and distance in the mental representation. It involves dumb activation and is automatic and continuous in that the current contents of working memory are continuously resonating with information sources.

Knowledge-based inferencing. Generating knowledge-based inferences (or elaborations) is going beyond information explicit in the text and involves accessing related knowledge, which may be incorporated into the mental representation.

Dumb activation. Dumb activation is a bottom-up process, as opposed to top-down, where prior knowledge related to the information in the text is activated regardless of whether it is relevant or irrelevant to the context.

Continuity monitoring. Readers monitor the sense of how well the current linguistic input fits with the prior discourse context. This sense of continuity is influenced by and can influence inference generation. Continuity monitoring may be the emergent state resulting from mapping.

Laying a foundation. Processing at the beginning of a discourse, episode, or sentence can require additional processing time. This phenomenon is referred to in the Structure-Building model as laying a foundation for the discourse structure, onto which subsequent discourse constituents are mapped.

Shifting. The Structure-Building model assumes that when a comprehender fails to make connections between constituents in a discourse, there may be a shift to a separate mental structure.

Suppression. Successful comprehension requires ignoring irrelevant information in the discourse, such as irrelevant meanings of ambiguous words. The process of focusing on relevant meanings, and discarding irrelevant meaning is referred to as suppression. Some theories assume that this occurs as a function of inhibiting the irrelevant meanings. Other theories propose that it is an emergent effect of enhancing the relevant meaning.

Resonance models have been described as mutually exclusive accounts of comprehension (Albrecht & Myers, 1995), it is generally accepted that they need not be (Graesser et al., 1994; Kintsch, 1998; Long & Lea, 2005; Myers & O'Brien, 1998; van den Broek et al., 2005; Wolfe, Magliano, & Larsen, 2005). When readers have a substantial amount of relevant background knowledge and the text is not overly difficult, mapping processes are most likely largely supported by automatic processes. However, in instances where there is a specific task that provides an explicit goal for reading, the text is difficult, or the information is relatively unfamiliar to the reader, deep comprehension most likely does require conscious and deliberate problem solving (Collins, Brown, & Larkin, 1980). This does not mean that readers will necessarily engage in effortful processing to achieve an adequate degree of comprehension. Nonetheless, educational contexts should presumably aspire to engender the ideal reader, such as that described by the Constructionist model.

One may find it perplexing that we designate text-based inferences as a common feature (see Section 1.3), but not knowledge-based inferences. It is well understood that knowledge-based inferences are at least important, if not central to comprehension (e.g., Graesser, 1981; Graesser et al., 1994; Kintsch, 1998). Indeed, as mentioned above, a central distinguishing factor between theories of discourse comprehension during the 1980s and early 1990s regards differences in predictions on what inference categories are routinely generated online during reading (see, for reviews, Graesser et al., 1994; McKoon & Ratcliff, 1992). Whereas most models discussed here specify assumptions that are related to text-connecting inferences, not all specifically describe assumptions related to knowledge-based inferences. For example, the Causal Network model exclusively focuses on text-based inferences rather than knowledge-based inferences.

Continuity monitoring is also important to successful reading. At least three theories specify that continuity monitoring is central to the theory. Continuity monitoring is a late, evaluative process that operates on the output from the mapping processes. It essentially involves an evaluation of the extent to which the current linguistic input fits into the prior discourse context. The Causal Network analysis describes this as an implicit evaluation of the extent to which there are necessary and sufficient causal antecedents available in working memory (Trabasso et al., 1989). However, a key feature of continuity monitoring is that it does not involve a conscious awareness of the cohesive features of the discourse that affect perceived sense of fit. Hence, continuity monitoring may be primarily supported by bottom-up processes, rather than strategic, top down processes.

There are three dimensions that are for the most part, uniquely assumed by the Structure-Building model, and are not explicitly included in many of the other models, laying a foundation, shifting, and suppression. Laying a foundation is the process of beginning to build a structure; shifting is the process of moving away from one structure to another; and suppression is the mechanism that allows the reader to avoid shifting, by inhibiting irrelevant information. The authors of the other six models may implicitly assume that at some points in comprehension, such as in the initial phases or at breaks in comprehension, the reader engages in effortful processes such as knowledge activation. However, none of the other models identify laying a foundation as separate from other phases of comprehension. Likewise, because the notion of shifting is tied to laying a foundation, there are few other models that include it within their assumptions. One exception can be seen in our judgment that shifting is a process that is central to the Event-Indexing model. This assessment was made because the continuity monitoring assumption of the model assumes that readers perceive that new episodes begin when there are breaks in multiple dimensions. There is evidence that breaks in multiple dimensions of situational continuity does lead to increased processing time (Zwaan, Magliano et al., 1995) and perceptions that there is an episode shift (Magliano et al., 2001). Nonetheless, these data do not necessarily suggest that shifting is necessarily a unique cognitive process.

Suppression is similarly a concept that has been focused on primarily within the context of the Structure-Building model. Notably, although negative links are not necessary to drive out irrelevant information in the CI model (McNamara & McDaniel, 2004; Rowe & McNamara, 2008), Kintsch (1998) also adopted the notion of suppression in the form of inhibitory links. However, few of the other models have focused on this concept or process (cf. O'Brien, Albrecht, Hakala, & Rizzella, 1995).

3.1.3. Products of Comprehension

Processes and mental operations give rise to various mental representations, each representing different aspects of comprehension (Balota et al., 1990; Graesser et al., 1994; Kintsch, 1988; Kintsch & van Dijk, 1978; van Dijk & Kintsch, 1983; Zwaan & Radvansky, 1998). Products of comprehension (see Tables 2 and 5) refer to mental representations resulting from comprehension processes, which can contain multiple levels of meaning (Fletcher, 1994; Graesser & Clark, 1985; Graesser et al., 1997; Kintsch, 1988; Kintsch & van Dijk, 1978; van Dijk & Kintsch, 1983; Zwaan & Radvansky, 1998). It is noteworthy that there is often a misconception that these products represent discrete representations which would be more aptly conceptualized as different aspects of the mental representation that is constructed for a discourse (Graesser & Clark, 1985).

There are two models that focus more on the qualitative and structural aspects of the products of comprehension, the CI and the Constructionist models. The focus on these products, particularly by the CI model, stems from it being one of the first models, and the one that is described in most detail. As such, these products of comprehension may very well be more or

Table 5 Definitions for Products of Comprehension that Vary in Importance Across the Seven Comprehension Models.

Situation model. To the extent that the textbase level of understanding is incomplete or includes implicit information, the comprehender must make inferences that go beyond the text. Those inferences can include inferred connections between separate parts of the discourse and links to prior knowledge. The situation model can be both local and global. That is, there can be a situation model level of representation for a sentence, and there can be a situation model representation for larger chunks of discourse, or an entire passage.

Propositional textbase. It is assumed that the comprehender constructs the deeper meaning of a sentence from the surface information (e.g., word, syntax). This deeper meaning is represented symbolically as a proposition, which is assumed in some theories to be the fundamental unit of processing. The proposition includes a core proposition with a predicate (e.g., verb) and arguments, as well as subpropositions (e.g., modifiers, situational semantics).

Levels of representation. A discourse representation is comprised of multiple dimensions, including the surface, textbase, situation model, and pragmatic levels. These levels of representation are not independent of one another, but together comprise the mental representation for a discourse.

Local coherence. This is an aspect of the comprehender's mental representation comprising the established relationships between the current linguistic input and the immediately prior discourse context or local chunks of text. The mental representation tends to be locally coherent to the extent that the comprehender has made connections between consecutive constituents in the discourse (words, ideas, sentences).

Global coherence. This is an aspect of the comprehender's mental representation comprising the established relationships between discourse constituents (sentence, paragraph) and the discourse as a whole. The mental representation tends to be globally coherent to the extent that the comprehender has established an organizational structure within a larger discourse context.

Sources of information. Information can be made available from several information sources, such as the current linguistic input, the prior discourse representation, relevant world knowledge, and other episodic memories. These are the building blocks for constructing the memorial representation.

Levels of comprehension. Comprehension can be conceptualized as existing on a continuum rather than as a discrete or holistic construct. Levels of comprehension can vary from reading situation to the next, over the course of reading a document, or over time (one may initially not fully understand a text, but engage in postreading processes that lead to a deeper sense of comprehension). Levels can be described in various ways such as surface versus deep, textbase versus situation model, and so on.

Hierarchically structured representation. The implicit and explicit relationships between discourse constituents lead to a hierarchically structured representation. Certain discourse elements will be central to the structure of the discourse in the memorial representation. For example, in some situations, readers may be sensitive to a hierarchical structure of the characters' goals. This concept is also captured within the macrostructure of the CI model.

less universally accepted by the authors of the other five models; however, they receive little to no focus in those five models.

Of the products, the one that most clearly stands out as central or important to most models is the situation model. Since this construct was first postulated (Johnson-Laird, 1983; van Dijk & Kintsch, 1983), it has arguably been a central focus of discourse comprehension research. This stems from the general assumption that deep meaning rests in the construction of a representation that reflects the implicit situation, rather than representing the explicit content.

Each of the theories may emphasize different processes that support the construction of a situation model. For example, the CI model emphasizes the role of knowledge-based inferences in the construction of a situation model, whereas the Event -Indexing and Causal Network models emphasize the role of text-based inferences that reflect situational continuities (e.g., causal, spatial, temporal). Clearly, both knowledge-based and text-based inferences are central to the construction of a situation model and a comprehensive theory must explain the processes that support both general classes of inferences.

It is somewhat surprising that only the CI model explicitly assumes that the representation of the text content is propositional in nature. Some models acknowledge this as an aspect of the representation, but allow other forms of representation, and some models leave it out entirely. This is aligned with the concepts of levels of representation, and the local and global coherence of that representation. While it seems that the field as a whole embraces these concepts, few models other than the CI model have focused on these aspects of comprehension.

Another dimension for which we found sparse mention within models is sources of information. At some level, we presume that all of the models assume that there are various sources of information during comprehension, specifically the discourse context (i.e., current sentence and textbase representation for the prior text) and relevant knowledge (world and episodic knowledge). These sources are the basis for the construction of inferences, the textbase, and situation model. Graesser et al. (1994) conducted a similar exercise in evaluating models, but on a much smaller scale. In doing so, they listed information sources as a common assumption. However, we found that only the Landscape model explicitly included this dimension and the CI model does so implicitly. Moreover, the Landscape model discusses information sources in lieu of the construction of the textbase and situation model (Tzeng et al., 2005). We believe that information sources should be treated differently than the constructs of the textbase and situation model because the latter imply a constructed mental representation, but the former do not. Rather, information sources are activated knowledge that contribute to the construction of these representations and fluctuate in activation as a function of features of the discourse (Todaro, Magliano, Millis, McNamara, & Kurby, 2008).

The other two dimensions that are not prominent across models are the notions of levels of comprehension and hierarchically structured representations. Levels of comprehension is a concept focused on primarily, again, by the CI model. Although it seems to be embraced by the field, there are few other models for which it is a focus. Nonetheless, it is a critical dimension to consider, particularly when devising measures to assess readers' comprehension. For example, researchers have often used the levels of comprehension construct to develop questions that assess understanding of explicitly conveyed information (i.e., the textbase) as contrasted with inferences that may have been generated to understand the text (i.e., the situation model; e.g., McNamara, 2007; McNamara & Kintsch, 1996a). As such, this construct has been useful in developing questions that enable researchers to assess different aspects of the mental representation for a text and thus afford more precise indices of how well a reader has comprehended a text.

The hierarchical structure of the readers' understanding is orthogonal to the notion of levels of representation. Within the context of the CI model, the hierarchical representation is captured most in the macrostructure. This structure emerges from the text as well as the reader's prior knowledge, and thus global inferences about the text. In the context of the Causal Network model, the hierarchical organization of mental representation can be conceptualized as an emergent property of text-based inferences, and in particular, causal inferences. For example, when characters have an explicit superordinate goal that guides their actions, causal inferences linking goals with subgoals and goals with actions create the hierarchical structure (Suh & Trabasso, 1993).

The notion of global coherence aligns somewhat to the hierarchical structure of the mental representation of the text. This is contrasted with local coherence which is more closely tied to the textbase representation. Local and global coherence have a rich history in discourse comprehension theory and research. These constructs took center stage when McKoon and Ratcliff (1992) proposed the minimalist hypothesis that readers only seek to establish global coherence when they fail to achieve local coherence. The Constructionist theory was, in part, posited in response to the minimalist hypothesis and Graesser et al. (1994) explicitly stated the assumption that readers have a drive to achieve both local and global coherence. Since this debate, it has been established that readers routinely establish both local and global coherence (e.g., Suh & Trabasso, 1993), which can be achieved in part via dumb, bottom-up processes (Myers et al., 1994).

Like the notion of hierarchical structure, we view local and global coherence as emergent properties of the inferential processes that support the construction of a situation model. That said, these constructs are important for research on individual differences in comprehension ability. Specifically, the comprehension processes of less-skilled comprehenders tend to operate on the local context (one or two sentences), whereas skilled comprehenders routinely engage in inferential processes that support the construction of a global coherent situation model (Cote & Goldman, 1999; Magliano & Millis, 2003; Millis, Magliano, & Todaro, 2006). Another way of viewing these processes is in terms of the reader's microstructure and macrostructure representation of the text. Local coherence is driven primarily by the microstructure and global coherence by the macrostructure (Kintsch, 1998).

3.1.4. Extratextual Dimensions

We use this category to refer to processes that are relatively high level, and that likely occur postintegration (though not necessarily). These are also more pragmatic processes, reflecting metalinguistic or social aspects of the reader or the reading context that can influence processing and the nature of the ensuing products (see Tables 2 and 6). It is clear that extratextual dimensions of comprehension comprise an underserved category. Only three models explicitly included any extratextual dimensions. Both the Constructionist and Causal Network models consider the reader's drive for explanation to be a critical component of comprehension and explanation-based processes are assumed to be central to mapping according to the Constructionist model (Graesser et al., 1994). These models assume that the process of explanation essentially underlies the comprehension process, such that the reader continuously strives to explain the information on the page. This claim contrasts with models such as the Resonance model, which assumes that most of comprehension occurs as a result of automatic memory retrieval processes, as well as evidence indicating that explanation-based processes occur after 500 ms (Long & Golding, 1993; Magliano et al., 1993; Till et al., 1988).

Only two models, the Constructionist and Landscape models, explicitly include more than one of the dimensions we have categorized as extratextual. This is linked to their focus on top-down processes, in contrast to bottom-up processes such as dumb activation. The Landscape model stands out as the only model that has attempted to simulate variations in readers' standards of coherence, which are assumed to emerge from factors such as the reader's purpose or goal for reading (Linderholm et al., 2004; van den Broek et al., 2005). There is a good deal of evidence that instructions given to readers, their goals, and their purpose for reading has substantial effects on reading processes and comprehension (Linderholm & van den Broek, 2002; Lorch, Lorch, & Klusewitz, 1993; Narvaez, van den Broek, & Ruiz, 1999; van den Broek et al., 2001). For example, van den Broek et al. (2001) found that readers generated more bridging inferences and paraphrases when reading to study, whereas they generated more elaborations and editorial remarks when reading for entertainment. As described in the review of the Landscape model, these variations in reading purposes, and consequent standards of coherence, are simulated by manipulating the activation values for elements involved in relations such as causal connections, such that those

Table 6 Definitions for Extratextual Dimensions that Vary in Importance Across the Seven Comprehension Models.

Goals. Some comprehension models such as the Constructionist model assume that reading is an inherently purposeful activity. As such, readers are assumed to always have a goal when reading a discourse. This goal varies in explicitness and discreteness. For example, a reader may have a vague and implicit goal to be entertained or a specific and explicit goal to identify explanations for some event provided by the authors.

Task. Reading may be contextualized within some larger task, such as learning for a class or to write a paper. The task can provide the goal or purpose for reading. Tasks are sometimes provided by some environmental context, such as school, work, and so on. The task involves some activity for which the information obtained from the reading will be used, such as a postreading activity (taking a test, writing a paper, answering questions, analyzing the text).

Affect. Affect refers to the reader's emotional response to the discourse. Readers can have emotional responses to reading including joy, amusement, frustration, and confusion.

Standards of coherence. Comprehenders are assumed, in some theories, to have a minimum threshold of comprehension that is being sought, called the standard of coherence. If a reader has a low standard of coherence, then understanding the discourse at a superficial or even incomplete level will be sufficient. Readers with a high standard of coherence will be more likely to generate inferences in order to understand the text at a deeper or more complete level. Readers' standard of coherence can vary as they read a text or it may be a source of individual differences in comprehension skill.

Evaluation of comprehension. This is the assumption that comprehenders routinely evaluate their sense of comprehension. This evaluative process will be guided by a standard of comprehension or coherence, which is also determined by comprehension goals.

Drive for explanation. Comprehenders are assumed to have a drive for a sense of explanatory coherence that comprises why events, actions, and states occur in a given context. Accordingly, comprehenders routinely infer causes of events and that the drive is controlled by an implicit evaluation of causal fit—are there necessary and sufficient antecedents available in memory? The drive for explanation becomes conscious and explicit when memory-based retrieval fails to activate necessary and sufficient causes.

Embodiment. A central assumption of theories of perceptual symbols is the notion that areas of the brain that are responsible for perceiving and acting in the world are also involved in knowledge representation. Processing language involves activating the perceptual and sensory/motor areas of the brain. Similarly, theories of embodiment assume that information processing is affected by the comprehender's understanding from the standpoint of the human body.

Imagery. Although comprehension models often represent discourse in terms of propositional, or via some other abstracted representational means, comprehension models assume that comprehension involve multiple modalities and modes of representation, including verbal, symbolic, and iconic modalities. The creation of images while understanding discourse is assumed to be fundamental process of comprehension.

readers who have lower standards of coherence are assumed to have lower activation values for those elements, and vice versa. Consequently, the reader with lower standards of coherence has a weaker memorial representation.

The final two processes that we have included as extratextual dimensions are embodiment and imagery. Embodiment is closely aligned with perceptual symbols theories (Barsalou, 1999a; Zwaan, 2004) that assume that the brain systems correlated with perceiving and acting in the world are also involved in knowledge representation, language processes, and event comprehension. It is certainly debatable if embodiment is a process in and of itself, or rather, a consequence of multiple processes. However, we consider perceptual symbols and embodiment as processes in the context of Barsalou's (1999b) Perceptual Symbols theory and Glenberg's (1997) theory of Embodiment. Both theories assume that perceptual symbols support comprehension through a process in which perceptual symbols are activated and mapped onto the discourse context through a process of simulation (see also Zwaan, 2004). Likewise, there is a growing interest in the influence of imagery on comprehension (Horton & Rapp, 2003). Certainly, all comprehension models assume that the reader is creating iconic images while reading (Kintsch, 1998). The alternative notion is simply ridiculous.

Nonetheless, there is growing recognition that these factors are not trivial for discourse comprehension (Dijkstra, Zwaan, Magliano, & Graesser, 1995; Graesser et al., 1997; Ohtsuka & Brewer, 1992; Tan, 1996), and in particular in educational contexts (Snow, 2002). Take for instance affect. Readers and viewers arguably experience narrative texts and films to gain an affective response (e.g., a sense of pleasure, suspense, fear). Moreover, a reader's level of engagement is very likely influenced by the degree and nature the affective response to a narrative.

Perhaps one could view the exclusion of extratextual dimensions from theory as a necessary sin of omission. The objective is to specify models such that they can be computationally implemented and it is challenging, to say the least, to quantify the impact of many of these factors on comprehension in a manner consistent with this objective. For example, the relationship between affective response and discourse processes is not yet completely understood: they may be related (Ohtsuka & Brewer, 1992) or they may be separate, but coexisting processes. However we contend that the state of the field is such that a comprehensive theory should postulate assumptions and parameters that are sensitive to these factors.

3.2. Correlations Between Models

Another way in which the ratings in Table 2 can be used is as a means to assess the correlations between the models (see Table 7). Again, these are not experimental data, but simply an interesting lens through which we can

Table 7 Correlations Between Models as Reflected by the Dimension Ratings in Table 3.

	Structure building	Resonance	Event indexing	Causal network	Constructionist	Landscape
Construction–Integration	−0.02	0.51**	−0.12	−0.02	0.08	0.19
Structure Building		0.20	0.09	−0.10	−0.44*	−0.02
Resonance			−0.24	0.06	−0.04	0.43*
Event Indexing				0.31	0.09	−0.06
Causal Network					0.43*	0.25
Constructionist						0.49**

*$p < 0.05$ and **$p < 0.01$.

view the models. Notably, the correlations are negatively biased because they do not include the common dimensions across all of the models (see Table 1), and rather solely the ratings in Table 2. Given the number of observations and the fact that these correlations are based on the authors' ratings, one should consider the magnitude and direction of the coefficients in additional to their alpha levels. Nonetheless, these distinguishing features reveal commonalities among the models.

First, we see in Table 7 that the CI model is correlated with only one other model, the Resonance model. This corroborates views expressed by several researchers that these two models are exemplars for *memory* models. It is somewhat surprising, nonetheless, that the CI model does not show higher correlations with the other models, particular given that the CI model provides the foundation for most of them. Although this result may emerge because we did not include the common dimensions between the models (which are core assumptions of the CI model), it may also reflect the other six models' focus on dimensions that were not specified in the CI model. This notion converges with the analysis of the models discussed with respect to Figure 3, in that the CI model has focused primarily on quadrants C and D, whereas the other models have focused primarily on quadrants A and B.

The Landscape model correlates with both the Resonance model and the Constructionist model, corroborating claims by van den Broek et al. (2005) that the Landscape model is consistent with both of these seemingly contradictory models. The Causal Network model correlates with the Constructionist model and has a moderate (although relatively high in the context of this matrix), but nonsignificant coefficient with the Event-Indexing model, likely reflective of not only the common foci of the models (on situation model construction) but also the professional links between the authors of the models.

Notably the Event-Indexing model was not significantly correlated with any other model, and only weakly correlated with the Causal Network model. These latter correlations likely reflect a common focus on situation model construction and the lack of significant correlation likely reflects that the Event-Indexing model focuses on aspects of the situation model generally ignored by other models. Indeed, since the publication of Zwaan and Radvansky (1998), the Event-Indexing model has had a dominant influence on situation model research.

The Structure-Building model is not correlated to any other models, and is negatively correlated with the Constructionist model. We found this surprising because, like the CI model, it can be characterized as a general processing framework for discourse comprehension and there is a large body of data supporting the assumptions of the model (Gernsbacher, 1997). There are at least three explanations for these low correlations. First, the processes of laying a foundation and shifting are unique to this theory (and arguably emerging properties) and mapping is a unique property not included in the correlations. Second, although the construct of suppression is evident in other models, the Structure-Building model places a unique emphasis on it. This is related to the third explanation, that the Structure-Building model is unique in its focus on the role of individual differences in suppression to explain individual differences in comprehension skill.

4. Summary of Model Reviews and Evaluations

The purpose of Sections 2 and 3 was to provide a framework for making sense of the broad theoretical landscape covered by the text comprehension literature. In Section 2, we provided a description of seven leading comprehension models. In Section 3, we examined dimensions that varied between the models. As is the nature of this relatively subjective evaluation provided in Section 3, there is nothing we have claimed that could not be debated. Yet, we have proposed platforms that hopefully allow the reader to view the models from various angles and perspectives. Regardless of whether we are right or wrong in our analysis, these perspectives provide novel means of considering and evaluating comprehension models.

What do we conclude from these perspectives? Several differences between the models emerged in our discussions. One controversy that has emerged regards the degree to which readers engage in explanation-based versus memory-based processes. Although these two perspectives have often been described as incompatible (e.g., Albrecht & Myers, 1995), they can also be conceptualized as describing different processes operating over the course of comprehension (Long & Lea, 2005; Magliano & Radvansky, 2001). Along these lines, van den Broek et al. (2005) provided evidence via a Landscape model simulation that cohort activation was aligned with the Resonance model (i.e., memory-based processes) whereas coherence-based retrieval processes were aligned with the Constructionist model (i.e., explanation-based processes).

The issue concerning explanation-based versus memory-based processes is related to the primary objective of virtually all models of discourse comprehension being to describe the general mapping processes that support the construction of a coherent text representation. There are several common assumptions that support mapping processes, but there is also some divergence across models. The majority of the divergence centers on whether mapping processes can be characterized either as bottom-up or top-down. We believe that neither perspective is mutually exclusive and that a comprehensive model must be able to describe when comprehension will be supported by effortful processes in addition to bottom-up processes.

The issue that has emerged consistently across many of the models regards the nature of and processes to build a situation model while reading. The concept of the situation model is most strongly associated with the CI model, which describes it as driven by an interaction between information in the text and activated prior knowledge, and notably, by the presence or absence of referential overlap. In contrast, the Event-Indexing and Causal Network models assume that the situation model captures an underlying event and causal sequence that takes place within a fictive time and place. These models by consequence place greater emphasis on the role of conceptual overlap among verbs as providing the primary basis for achieving coherence rather than coreference between referents or arguments (Zwaan, Magliano et al., 1995). We propose that this difference between the two classes of models results from differences in research foci (e.g., expository vs narrative text comprehension) rather than fundamental differences between the models. This observation leads to an interesting, yet untested, prediction that whereas variation in referential cohesion should affect expository text comprehension (McNamara, Louwerse, McCarthy, & Graesser, 2009), verb and causal cohesion may have a greater impact on narrative (and perhaps history) text comprehension (McNamara, Graesser, & Louwerse, 2008).

Our driving claim is that the differences across the models discussed here stem primarily from differences in terms of the foci of the models and from describing different comprehension situations. For this purpose, in Section 2, we described the models in terms of their foci in reference to Figure 1. First, the CI model tends to be more concerned with quadrants C and D (i.e., more challenging, expository texts). In contrast, most of the other models focus on easy reading (e.g., narrative) and ideal readers (e.g., college students in top schools) represented by quadrants A and B (i.e., narrative and descriptive texts). The Structure-Building model focuses somewhat on explaining individual differences in comprehension skill, and thus might be considered to cover both quadrants A and B. We reasoned that the Resonance Theory falls somewhere in the middle of quadrants A and B in that it describes neither the highly motivated or strategic reader nor the minimalist reader. The Event-Indexing and Causal Network models, by contrast, focus on readers in quadrant A, namely relatively skilled readers confronted with relatively easy texts. Finally, the Constructionist and Landscape models come closest to covering all four quadrants, though for different reasons. Overall, the majority of the models place greater focus on conscious, goal-driven processes, and on events and actions. In contrast, the CI model, in the context of primarily informational text, has focused more on bottom-up activation processes, and less so on conscious processes. And, there is a greater focus on conceptual content, such as that provided by arguments (e.g., nouns), rather than the effects of events and actions (e.g., predicates, verbs).

With respect to Figure 1, the current models provide a good start in describing processes across the four quadrants. However, it seems that these leading theories do not address the same types of readers nor do they investigate comprehension using the same types of texts. Clearly, comprehension will vary along these dimensions, and experimental results will be influenced by these dimensions. Further, we observed in Section 3 that the models uniformly ignore both the lowest and highest levels of comprehension. That is, there has been little to no focus on the reading process (e.g., decoding and parsing), and even less focus on extratextual aspects of comprehension. We discuss these issues as well as what a comprehensive model of comprehension would need to more fully consider in more depth within the following section.

5. Toward a Comprehensive Theory of Comprehension

Our ultimate goal is to outline a comprehensive model of comprehension that extends upon the CI model and contains features specified by the other six models. This model should be able to account for the varied comprehension situations depicted in Figure 1. A comprehensive model should be able to account for not only situations where demands are low, such as quadrants A and B, but also when processing demands high, such as quadrants C and D. One could argue that the CI and Landscape models can make these distinctions. However, none of the implemented models can account for strategic processing, although the implementation of the parameters associated with standards of coherence within the Landscape model is a step in the right direction. Moreover, none of the models can account for the individual difference factors or contextual factors that would lead to readers falling in quadrants A and C versus D.

Although our ultimate goal is to push the field toward a more comprehensive model that can account for these different reading situations, it is critical that a comprehensive model be implemented computationally. One attractive feature of the CI model is that it can account for many aspects of discourse comprehension with a relatively small set of assumptions and parameters in the implemented model. However, as is evident in our discussion thus far, a comprehensive model would have to go beyond the CI model to account for the reading situations depicted in Figure 1. The overarching purpose of the analysis presented above was to work toward an understanding of what each of the seven models offers in their explanations of the processes underlying comprehension, to identify commonalities and differences between models, and to identify missing components. In this section, we outline the directions we consider most important to include in what might provide a more comprehensive model of comprehension. However, tough decisions will have to be made so that a comprehensive model can be implemented.

Our starting assumption is that the common features listed in Table 1 need to be explicitly part of a comprehensive model and it is the dimensions that vary across models that must be carefully considered for inclusion in the comprehensive model. Many of these features support basic processes that fall into quadrant B and operate more or less in the other quadrants. In an effort to narrow down explicit features, we first discuss the dimensions discussed above that need to emerge from the explicit features and processing assumptions of a comprehensive model. Next we discuss the nonconsensual features, processes, products, and extratextual components of comprehension that were discussed above and that should be explicitly part of a comprehensive model. We then discuss dimensions of comprehension that have been ignored by most if not all of the comprehension models, but need be considered in more comprehensive models of comprehension. These include cognitive features and processes relevant to decoding and parsing, extratextual aspects of comprehension, individual differences in comprehension skill, and processes involved in the comprehension of alternative modes of communication.

5.1. Emergent Properties of Models

There are some dimensions of models that can be considered emergent properties, rather than processes, products, or rules that must be implemented in the model (Rumelhart & McClelland, 1986; Rumelhart, 1984). Connectionists have claimed that many behaviors that have the appearance of being rule based may be emergent from the operations of lower-level features. In the context of purely connectionist models, virtually all of the dimensions we have discussed might be emergent. Here, we operate at a higher level of scrutiny by considering those properties that could or should fall out of the model in that they or their effects are apparent as a result of other dimensions of the model.

We have argued here that some, but not all, of the models' dimensions may emerge from explicit features and processing assumptions that should be explicitly part of it. One approach toward a level of parsimony in a comprehensive model is to identify which dimensions can be considered emergent properties of other dimensions. Also, some properties should emerge from the system, as a test of the fundamental assumptions of the model.

Thus, in this section, we identify emergent dimensions among those we have considered. We have included five processes (dynamic activation, continuity monitoring, laying a foundation, shifting, suppression) and four products (levels of comprehension, local coherence, global coherence, hierarchical structured representation). We assume that features, at least those we considered here, cannot be emergent properties because features by necessity must be implemented.

The first process we consider emergent is the notion of the dynamic fluctuation of activation. This is relevant to changes in activation values in the course of comprehension such as described by the Landscape model (e.g., van den Broek et al., 1999), as well as to the notion of different mental models as proposed by the Event-Indexing model (i.e., the current, integrated, and complete models; e.g., Magliano, Zwaan et al., 1999). We believe that dynamic fluctuation of activation is a feature that emerges from at least two processes. The first is memory-based retrieval (Myers and O'Brien, 1998). That is, given that the content of working memory naturally changes across sentences in a discourse, the retrieval cues will change. As such, the activation of knowledge sources fluctuates across sentences. Additionally, dynamic activation occurs via the mapping processes and text-based inferences (Magliano, Trabasso et al., 1999; Langston & Trabasso, 1999; Langston et al., 1999). When relationships are established between the current sentence and the nodes in the discourse representation, there are implications regarding the availability of nodes in the entire network (Langston & Trabasso, 1999; Langston et al., 1999). Thus, dynamic activation is an aspect of comprehension that emerges from changes in the retrieval cues (e.g., the text itself) and changes in concepts' activation levels resulting from mapping and inference processes.

The second dimension that we consider emergent is continuity monitoring. Within our definition in Table 4, we state that continuity monitoring may emerge from the mapping processes. Readers are consciously aware of the output from the mapping processes. When relationships between the current sentence and the prior discourse context are established, there is a sense of fit, whereas readers will be aware of a lack of fit when relationships cannot be established (Magliano, Zwaan et al., 1999). Moreover, this construct has substantial overlap with the metacognitive process of evaluating one's sense of comprehension. As such, there may not be a need to specify a feature or parameter in a comprehensive model that corresponds to continuity monitoring, though it need emerge from the assumptions of the model.

The three processes proposed by the Structure-Building model, laying a foundation, shifting, and suppression, may also be viewed as emergent. Gernsbacher (1990, 1997) interprets the effects of comprehension processes involved in laying a foundation as revealing processes unique to comprehending information after the initial sentence, clause, or picture. Alternatively, these effects can be interpreted as emergent properties of constraint-based connectionist systems such as the CI model (Kintsch, 1998). One problem with the Structure-Building interpretation is that it implicitly requires that the comprehender be aware of beginnings of and changes in episodes, or that somehow, this separate process of laying a foundation kicks in automatically. Alternatively, the evidence observed in support of comprehenders laying a foundation can be viewed in terms of three phenomena. First, the lack of background information at the start of a discourse means that there is no information primed, and there is no information to link back to and as such, processing will necessarily take longer (McNamara & Kintsch, 1996b). Second, the network will be more sparse because there are fewer textual cues and there is no information previously activated. A sparse network is less coherent, and thus takes longer to settle and is less stable. Thus, this aspect too will lead to longer times to process the information. Third, because there is no related information previously activated, there will be less interference. This lack of interference will result in primacy effects. Due to release from proactive interference, these effects would also be observed at the change of an episode.

Notably, these three phenomena could be viewed as compatible with the Structure-Building framework. Nonetheless, rather than viewing the effects associated with shifting as a need to create a new substructure, they can also be viewed in terms of two processes within the CI framework. First, gaps in discourse cause a break in the model, as described earlier. Second, when this occurs, the reader must make inferences to make connections to prior discourse or knowledge, or the reader continues without making connections. In the first case, those inferences take time to the extent that the knowledge is not readily available, but do not take extra time when the context and content is highly familiar (Ericsson & Kintsch, 1995). In the second case, the network will be sparse and lack connections, which takes more time to settle (i.e., corresponding to longer reading times). These explanations may be consistent with the Structure-Building model, but they run counter to the assumption that laying the foundation and shifting entail unique processing.

Whether suppression may or may not be an emergent property is a question of parsimony, but it is also a theoretical choice. The notion of suppression in the Structure Building is captured in an inhibition mechanism that allows skilled readers to ignore irrelevant information. Because negative links are needed, inhibition would not be an emergent property of connectionist systems. However, McNamara and colleagues (McNamara, 1997; McNamara & McDaniel, 2004; Rowe & McNamara, 2008) have shown that suppression can emerge without negative links (or inhibition) within the CI model by assuming that suppression results from greater activation of relevant information which results in a more coherent situation model representation. Based on research showing that skilled comprehenders make more inferences to prior discourse and to prior knowledge (e.g., Long, Oppy, & Seely, 1994; Oakhill & Yuill, 1996; Whitney, Ritchie, & Clark, 1991), McNamara (1997) assumed that less-skilled comprehenders activate a minimal number of extrasentential concepts to understand the target sentence, whereas skilled comprehenders activate more concepts that are not explicit in the textbase. In sum, skilled comprehenders construct a more coherent, richer situation model when reading because more inferences are generated and more knowledge is activated. Replicating Gernsbacher's results, the network representing the less-skilled reader took more time to suppress the irrelevant meaning of the ambiguous words, and the network representing the skilled readers took less time, without including negative links between the relevant and irrelevant meanings (see also Rowe & McNamara, 2008; cf. Kintsch, 1998). McNamara and McDaniel (2004) further showed that differences in the ability to suppress irrelevant information also emerge as a function of prior knowledge. When the reader has more prior knowledge, irrelevant meanings of ambiguous words are suppressed more quickly, regardless of reading skill. Thus, greater activation of knowledge results in faster suppression of irrelevant concepts.

It is important to note that McNamara's (1997) explanation does not rest on more or less activation of the relevant meaning of any particular word, nor does it predict greater activation of the relevant interpretation of the sentence. Gernsbacher and Faust (1991) demonstrated that the meaning of the ambiguous word is not more or less activated as a function of comprehension skill. For example, they demonstrated that skilled and less-skilled comprehenders showed equivalent facilitation for the appropriate meaning (*GARDEN*) in a biased context, *He dug with a spade*, compared to an unbiased context, *He picked up the spade*. However, McNamara's (1997) simulation of Gernsbacher and Faust's data showed that these differences emerged from interference from the irrelevant interpretation of the sentence (for less-skilled comprehenders) and not because of differences in facilitation at either the lexical level or the propositional level. Rather, McNamara's interpretation rests on the notion that without a coherent situation model representation of the sentence, the irrelevant interpretation of the sentence remains activated. By contrast, the increased associations in the skilled comprehender simulation essentially take over the network such that the irrelevant meanings more quickly die out. The lack of competition for resources between relevant and irrelevant interpretations results in residual activation for the irrelevant meaning of the ambiguous word. Accordingly, less-skilled comprehenders do not use resources effectively, whereas skilled comprehenders' maximal use of resources drives out irrelevant information.

In sum, we have included four products to be considered as emergent properties. One might argue that all products should emerge from explicit features in the model; however, we have included only those products that are dimensions of the quality of the reader's mental representation. The first is that of levels of comprehension. This is a concept closely tied to the CI model, which postulates that different aspects of the readers' mental representation are more or less dominant, and this dominance is reflected in various measures that tap into the various levels of the mental representation. For example, if the reader has focused primarily on the explicit concepts on the text, and has not generated abundant inferences, then the textbase-level representation would be expected to be more fully developed, whereas the situation model representation (depending on the text) would be weaker. These aspects are expected to be apparent via different types of comprehension measures (e.g., van den Broek, 1994). Recall and text-based questions tap the reader's textbase-level representation and measures such as bridging inference questions, sorting tasks, and problem-solving questions are assumed to tap the situation model representation. Because levels of comprehension emerge from the reader's comprehension processes and from the representation built by the reader, we consider it to be emergent.

Likewise, the notions of local and global coherence are descriptions of relationships or the nature of the mental representation. As stated above, the distinction between these two has a long history and has been important for distinguishing between theories (e.g., Graesser et al., 1994; McKoon & Ratcliff, 1992; Singer et al., 1994). However, this is arguably no longer the case. To elaborate, some have treated local and global coherence as referring to establishing relationships between adjacent and distal constituents (e.g., McKoon & Ratcliff, 1992). As such, the constructs of local and global coherence can be considered a classification of different distances that can occur with respect to established relationships between discourse constituents (established through coreference or text-based inferences). It is important to note that others have conceptualized global coherence as a property of a representation that enables readers to derive an overarching, organizational structure (e.g., Graesser et al., 1994). Nonetheless, we still view it unnecessary to implement formal assumptions regarding global coherence in a comprehensive model because it is just that, a property of the representation that should emerge from features and processes assumed within the model.

We also consider the construct of hierarchical representations as a description of the nature of discourse representations. This aspect emerges when a discourse constituent(s) (e.g., explicit character goal) becomes central to the representation because it is related to many other discourse constituents. For example, in a James Bond movie or novel, the character is given a goal at the beginning of the story and that goal becomes an organizing feature of the plot structure. The node reflecting that goal is the highest node in the hierarchy. However, it takes on that status as a result of mapping and text-based (i.e., causal) inferences. It is important to note that not all texts afford a hierarchically structured representation and as such, this is driven by features of the discourse.

In this section, we have considered which dimensions need not be implemented explicitly in a comprehensive model, but may be expected to emerge from other dimensions. We consider it important to discriminate in a model between those dimensions that must be implemented and those that are emergent dimensions of a model; first, because emergent properties should essentially fall out of the model, or emerge from the fundamental features and processes assumed within the model, and, second, because such an approach leads to a more parsimonious model. In the following sections, we consider dimensions of comprehension that are lacking from current models but should be considered in a more comprehensive model of comprehension.

5.2. Features of the Discourse

It is important for a comprehensive model to explain how features of the discourse guide processing. As discussed in the evaluation section, two features of text have been considered in depth thus far in the comprehension literature: referential cohesion and situational cohesion. We consider these two features both to be fundamental dimensions of comprehension.

However, morphology-, syntax-, and sentence-level semantics (i.e., situational semantics) have largely been ignored in formal models of comprehension. As we have already discussed, this is largely due to the fact that most theories focus on mapping processes that presumably operate after the meaning of a sentence is computed (i.e., after the computation of a propositional representation). However, given the growing body of evidence that morphology and syntax guide processes such as mapping and situation model construction (Carreiras, Carriedo, Alonso, & Fernandez, 1997; Givon, 1995; Magliano & Schleich, 2000; Morrow, 1985, 1986), we believe that a comprehensive theory must take into account the impact of these features on discourse comprehension.

One challenge stems from the fact that discourse analyses are sometimes necessary to identify the presence of these features. These analyses can be labor intensive and require specialized training. An alternative would be to have the comprehensive model rely on computational linguistics to analyze the presence of features that guide processing, rather than human judges. A means of doing so is provided by tools such as Coh-Metrix (Graesser et al., 2004; McNamara et al., 2009). Coh-Metrix is a tool that provides numerous indices of language automatically. Coh-Metrix uses lexicons, part-of-speech classifiers, syntactic parsers, latent semantic analysis, and several other components that are widely used in computational linguistics. For example, the MRC database is used for psycholinguistic information about words (Coltheart, 1981). WordNet has linguistic and semantic features of words, as well as semantic relations between words (Miller, Beckwith, Fellbaum, Gross, & Miller, 1990). Syntax is analyzed by syntactic parsers, such as Apple Pie (Sekine & Grishman, 1995) and Charniak's parser (Charniak, 2000), whereas the Brill's (1995) part-of-speech tagger identifies the syntactic classes of words, including unknown words on the basis of syntactic context. Coh-Metrix currently analyzes texts on three major categories of cohesion: coreference, conceptual (LSA), and connectives. It also provides features of words, such as frequency, concreteness, and polysemy, as well as the density of various classes of words. Of course Coh-Metrix *itself* should not be included within a comprehension model. Coh-Metrix simply provides information about the text using artificial intelligence techniques. However, analyses using such tools can inform which features are important in target texts and how they may differ from a larger class of texts. Also, the types of tools used in Coh-Metrix may lead to greater sophistication in comprehension models, affording the inclusion of a wider range of features using more objective and efficient methods.

Another approach that may afford accounting for lower-level features is the use of algorithms such as latent semantic analysis (LSA), which can be used to simulate word and world knowledge (e.g., Landauer, McNamara, Dennis, & Kintsch, 2007). LSA computes the semantic similarities between words, sentences, and paragraphs using statistical representation of world knowledge based on corpus analyses (Landauer & Dumais, 1997; Landauer et al., 2007). There are many algorithms similar to LSA that have been developed to extract meanings of words by using first or second-order co-occurrence from large bodies of text (e.g., Griffiths, Steyvers, & Tenenbaum, 2007; Jones & Mewhort, 2007; Landauer et al., 2007). More recent endeavors have centered on extracting not only semantics but also syntactic constraints of words, and thus the spectrum of lexical knowledge. One implication from this research is that knowledge about a word is extracted from experiencing the word in a variety of contexts, and thus the meaning of the word is captured in those experiences, and from the word's relation to other words. Words' meanings are generally thought of as "located" in a high-dimensional space relative to other words (or concepts and ideas). This assumption is quite similar, and at least compatible, with assumptions that a lexicon cannot contain all of the necessary information about a word (Elman, 2004, 2009).

In sum, one reason lower-level features have been ignored is due to challenges of implementation. Another reason for which lower-level features germane to word and sentence processing have been ignored in comprehension research regards a separation of fields of study and a consequent difference in computational approaches. Researchers in the area of language learning focus largely on how semantic and syntactical knowledge is acquired; thus, the majority of the computational models are connectionist learning models (e.g., Chang, Dell, & Bock, 2006; Elman, 1993; McRae, Spivey-Knowlton, & Tanenhaus, 1998). These models tend to focus on how humans can learn semantic and syntactic knowledge about words, and how this knowledge manifests in the understanding of syntactically ambiguous sentences. As such, the computational models are of a very different nature and focus than are models of text and discourse comprehension. In comprehension models, by contrast, all of the knowledge about the lexicon (semantic and syntactic) is assumed to have been already learned, and the model focuses on how knowledge is used to understand larger bodies of text and discourse (i.e., beyond the word and the sentence). Thus, these hybrid-connectionist models assume that an underlying layer could be attached to any comprehension model, such that the reader begins with relatively successful word and sentence understanding.

Thus far, this approach has been largely successful. Yet, it may no longer be viable if the goal is to develop a comprehensive theory of comprehension. One reason to consider lower-level features regards the issue of the dynamic nature of language and discourse understanding. Namely, comprehension processes occur over time, change and fluctuate over time, and show rapid, sometimes instantaneous access to multiple sources of information. This rapid, online access to knowledge cannot be easily explained within hybrid-connectionist architectures. Future accounts of comprehension may need to turn to theories of word and sentence understanding, and purely connectionist architectures (e.g., recurrent networks) in order to fully account for comprehension.

Another reason to more explicitly consider lower-level features regards the notion of emergent properties (Rumelhart & McClelland, 1986; Rumelhart, 1984). Some aspects of comprehension may emerge from features and processes that occur at the word and sentence levels. Rule-based computational models do not seem viable in the long run because of the vast number of rules and situations that would need to be accounted for within the model. Essentially, both lower-level and higher-level models need contend with the same problem: how does the reader access such a vast body of knowledge so quickly. One possibility is that consideration of the knowledge that seems to reside at lower levels of cognition may inform higher-level models; and vice versa.

5.3. Comprehension Processes

As is evident from the discussion of the models, there has been a debate regarding the extent to which mapping processes can be guided by dumb, bottom-up processes or effortful processing. Our conclusion from this literature is that when texts are relatively easy (quadrants A and B), the mapping can be considered primarily a bottom-up process. As such, the nonemergent processes of dumb activation, integration/settling, and memory retrieval would be necessary components of a comprehension model. However, it may be the case that mapping processes must be supported by effortful strategic processes in addition to bottom-up processes when the text are difficult and when the reader has the disposition to read strategically (e.g., quadrant C). However, parameters in a comprehensive model that correspond to effortful processing are more appropriately categorized as *extratextual* because these processes are likely to be driven by the goals or disposition of the reader, which are discussed in Section 5.5.

There is little controversy regarding the need for comprehension models to account for both text-based and knowledge-based inferences, and in particular for the former which contributes to mapping. The CI and Landscape model and the computational version of the Causal Network model provide excellent examples regarding how text-based or knowledge-based inferences can be generated via bottom-up inference processes. With respect to text-based inferences, there is still a need for the use of discourse analyses to identify where these inferences are likely to occur (Langston & Trabasso, 1999; Langston et al., 1999). Developing a computational model that can automatically detect causal or other relationships is still a long way off. Nonetheless, a comprehensive theory can rely on these connectionist-based approaches for specifying the bottom-up processes that support inference generation. However, as suggested in Figure 1, effortful processes can impact inference generation, depending on the nature of the text and the motivation of the reader. A comprehensive model must be able to account for these situations. As such, approaches for modeling the influence of effortful processing on inference generation is discussed in Section 5.5.

5.4. Products of Comprehension

As is evident in our discussion of emergent properties in Section 5.1, we contend that many of the dimensions associated with the product of comprehension represent descriptions of mental representations and should not be explicitly part of a comprehensive model, but rather should emerge from fundamental assumptions of the model. However, it is debatable whether the notion of levels of representation and the related constructs, textbase and situation models are emergent properties or instead necessitate explicit assumptions. It is possible that these could emerge from lower-level features (such as the words and syntax) in combination with assumed processes that act on those features. But this remains to be tested, because there are as yet no such models. An argument that they are not emergent stems from the necessity to assume that there are different forms of representation, and that they have different qualities and features. Also, levels of representation, including the textbase and situation model representations play integral roles in both theoretical and empirical aspects of discourse comprehension. Moreover, these constructs are central to understanding differences in the memory representations in the four quadrants in Figure 1. For example, the relative strength of the situation model should be high for reading situations in quadrant A, but relatively low in quadrant C.

5.5. Extratextual Dimensions

Very few models have considered extratextual features, and only one feature, standards of coherence, has been implemented formally (i.e., within the Landscape model). Nonetheless, comprehension involves more than just the text. It includes the reader, the tasks or activities, and the social context of the comprehension process (Snow, 2002). The strategies that the reader uses (and does not use), the reader's metacognitive awareness, and the reader's goals are a few examples of the extratextual dimensions that have large effects on reading comprehension (e.g., McNamara, 2007). Yet, a good majority of text comprehension research has centered on explaining comprehension processes germane to text, without considering these extratextual dimensions. Essentially, the reader is often left out of the equation. Consequently, a critical aspect of reading that is painfully lacking from comprehension models is the notion of the reader's free will. Readers are not passive buffers that take in text, process it, and spit out a representation. Readers make conscious decisions to engage in a wide variety of actions. They decide to start reading, stop reading, skim text, read deeply, focus, not focus, outline, reread, go back to the beginning, skip to the end, and so on. They have goals and they often prepare to engage in specific tasks after reading. They read individually and in groups, and they sometimes share common goals with others in their social context. They ask each other questions and sometimes even seek answers.

These more pragmatic, effortful, and even less effortful aspects of the comprehension process are noticeably absent components of comprehension models (McNamara, 2007). One reason for this absence is that our understanding of reading is based primarily on reading in the laboratory, where we sit the participant down, give instructions to read, and the participant appears to cooperate (at least by moving the eye and turning pages). This approach leads to an understanding of comprehension relatively void of either pragmatics or effortful, strategic processing.

Another reason why extratextual dimensions have not been incorporated is because we have an incoherent understanding of the processes involved. Although there is an increase in attention on the interactive natures of the reader, the text and the task, little has yet been done with regard to social context. We have a somewhat better understanding of effortful processes. For example, comprehenders' drive for explanation is clearly an important component of a comprehensive model. First, there is considerable evidence that event comprehension can be both guided and improved by explanatory processes (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Hilton & Slugowski, 1986; Magliano & Radvansky, 2001; McNamara, 2004; Trabasso & Magliano, 1996; Trabasso & Suh, 1993), which was the motivation for incorporating it into the Constructionist model. Second, in some situations, explanation is important for causal reasoning (Trabasso & Magliano, 1996; Trabasso & Suh, 1993).

The primary challenge to explicitly incorporate pragmatic and explanatory processes into a comprehensive model is to establish how they can be implemented. One way to implement changes as a function of pragmatic or goal-driven processes is to assume the consequences of those processes, and then implement those consequences within the model. For example, effects of variations in standards of coherence (e.g., as a result of reader goals) have been successfully simulated in the Landscape model by changing the activation values of elements in the text (Linderholm et al., 2004; van den Broek et al., 2005). However, this approach does not offer a satisfactory explanation for how those activation values become higher. Because the activation values are decided by the experimenter, they do not emerge from more fundamental assumptions in the model. It is not clear what cognitive processes could be responsible for activation values of concepts to have higher activation values before the information is processed (unless this is assumed to emerge from word- and sentence-level processing that occur somehow prior to comprehension processes).

By contrast, the Resonance model (O'Brien & Myers, 1999) makes the assumption that activation values are driven by the number of features linked to the concept. A greater number of features linked to a concept results in greater resonance to the contents of working memory. Accordingly, the likelihood of recalling an item is driven by the number of links to that item (via features). This is somewhat unsatisfactory as a solution because it leaves out exactly what a feature is and how it became linked to the concept.

Along similar lines, McNamara (1997; McNamara & McDaniel, 2004) assumed in the context of the CI model that one source, if not the principal source, of an increase in concepts' activation levels results from greater associative processing. That is, when more related concepts are activated, that feeds activation to concepts in the text. As such, it would be assumed that a higher standard of coherence results in more inference generation and more elaborative processing, and these associations result in a more coherent network, and higher activation levels for key concepts in the text. This same assumption would be made for readers with greater prior knowledge or higher reading skill, who tend to activate more knowledge or make more inferences while reading. This approach aligns with the notion in the CI model that situation model construction is critical to deep comprehension. Thus, whereas the Landscape model focuses on the explicit concepts in the text, and how relations drive activation, the approach by McNamara would extend the cause of differences in comprehension to the degree to which the comprehender went beyond the text.

These examples illustrate cases where the researcher makes assumptions about the outcome of the reader's behaviors, but the behavior itself is not in the model. In the case of the Landscape model, the activation values are changed, and in the case of the Resonance model (O'Brien & Myers, 1999) and McNamara's (1997) knowledge-based simulation, the researcher needs to include those associations within the constructed network. These approaches are somewhat unsatisfactory because the models' predictions do not emerge from processing assumptions within the model outside the subjective control of the researcher (see, e.g., Frank, Koppen, Noordman, & Vonk, 2008, who elaborate on this potential weakness of models).

One alternative approach would be to combine the connectionist architecture with a symbolic rule-based system. For example, within the Constructionist model, these types of processes were articulated within production rules. Similarly, in a CI-based model developed to simulate a problem-solving task, Doane et al. (2000) combined the CI model with a production rule system. They included a separate layer in the system that essentially sat on top of the Construction–Integration process, which assessed the state of comprehension and task completion, which in turn resulted in the activation of consequent behaviors. Essentially, certain behaviors or actions would fire depending on the state of the system. Such a system could be implemented to simulate goal-driven behaviors in comprehension by assuming that such behaviors, thoughts, or actions occur postintegration of the current information (e.g., after each sentence or clause). These production rules could fire other rules, which might result in a variety of behaviors such as continuing reading, rereading, activating related knowledge, searching the text, and so on.

While this is a viable solution, formalizing a sufficient set of production rules to explain the wide variety of phenomena and interactive effects that may emerge in varied reading situations could be unyielding, or at best a very long task. Also, an important issue to consider is whether using production rules is an artificial solution, and whether these more conscious behaviors can emerge from some other, more basic dimensions of the model.

So far this discussion has centered on issues surrounding the simulation of goal-driven, effortful processes during comprehension. Another important issue regards the effects of processes related to imagery and the relationship between the information in the text and the reader's body. There is a growing body of evidence that language processes are supported by the activation of perceptual symbols and embodied cognition (Glenberg, 1997; Glenberg & Kaschak, 2002; Madden & Zwaan, 2003; Stanfield & Zwaan, 2001; Zwaan, 2004; Zwaan, Madden, Yaxley, & Aveyard, 2004; Zwaan, Stanfield, & Yaxley, 2002). An argument could be made that a comprehensive model should contain explicit assumptions regarding how perceptual symbols and embodiment guide comprehension. However, we think this may be premature. First, to date, the research in support of embodiment is restricted to word- and sentence-level processing. Thus, we do not have a clear understanding of the impact of these factors on processes germane to comprehension of larger bodies of text. Second, to our knowledge, there is no computational model that has been produced that incorporates these constructs. Third, we adopt the perspective that a connectionist framework is the best approach for a comprehensive model. The nodes in a connectionist model could correspond to perceptual symbols; however, exactly how they would operate differently from how nodes currently function in a connectionist model of comprehension, such as the CI model, is unclear. At this point, we are left with the unsatisfying conclusion that our understanding of the construct of perceptual symbols and how they operate to support comprehension is not sufficient to implement them into a formal model. We strongly suspect that this will change in the coming years.

5.6. Comprehension Skill Differences

A comprehension model should be able to explain individual differences in comprehension skill: what do good comprehenders do differently than less-skilled comprehenders? However, few of the models attempt to explicitly explain or account for the comprehension skill differences, and none have done so considering the broad spectrum of situations depicted in Figure 1. Rather, most of the comprehension models that we have considered here focus on general comprehension processes, assuming an average reader in an average situation reading some given type of text (within one or two quadrants in Figure 1). Thus, too little attention has focused on accounting for individual differences in comprehension ability in the context of comprehension models.

What are the signatures of comprehension skill? The ability and tendency to generate inferences is likely the most critical difference between skilled and less-skilled comprehenders. Skilled readers also more successfully resolve anaphoric reference, select the meaning of homographs, process garden-path sentences, make appropriate inferences online, and integrate text structures (e.g., Long & Golding, 1993; Oakhill, 1983; Singer, Andrusiak, Reisdorf, & Black, 1992; Singer & Ritchot, 1996). Skilled readers are also more likely to generate inferences that repair conceptual gaps between clauses, sentences, and paragraphs, whereas less-skilled readers tend to ignore gaps or fail to make the inferences necessary to fill in the gaps (e.g., Garnham, Oakhill, & Johnson-Laird, 1982; Long et al., 1994; Magliano & Millis, 2003; Magliano, Wiemer-Hastings, Millis, Muñoz, & McNamara, 2002; Oakhill, 1984; Oakhill & Yuill, 1996; Oakhill, Yuill, & Donaldson, 1990; Whitney et al., 1991; Yuill & Oakhill, 1988; Yuill, Oakhill, & Parkin, 1989). Less-skilled readers are also less likely to generate topic related inferences and less likely to integrate incoming information with preceding discourse (e.g., Long et al., 1994). Consequently, less-skilled readers perform poorly on questions that address text-based or implicit inferences, even when the text is made available while they answer the questions (Oakhill, 1984).

Skilled comprehenders read in a goal-directed fashion and are able to strategically adjust how they read based on those goals (Gaskins, Satlow, & Pressley, 2007; Pressley & Afflerbach, 1995; Pressley, Forrest-Pressley, Elliot-Faust, & Miller, 1985; Pressley & Woloshyn, 1995). Moreover, they demonstrate better awareness of reading strategies and are better able to indicate when reading strategically is appropriate (O'Reilly & McNamara, 2007b; Taraban, Kerr, & Rynearson, 2004; Taraban, Rynearson, & Kerr, 2000). This underscores the importance implementing into a comprehensive model the extratextual dimensions that correspond to the evaluative and metacomprehension processes associated with a drive for comprehension, standards of coherence, and comprehension evaluation.

There have been several mechanisms proposed to account for comprehension skill differences (see, for a review, McNamara et al., 2008). The first, and the only one in the context of a comprehension model, is suppression (Gernsbacher, 1990). However, as we discussed earlier, there is evidence that suppression may emerge from inference processes (McNamara & McDaniel, 2004) and the research in support of inhibition was limited to psycholinguistic paradigms which typically involve processing only one or two sentences. The second proposed explanation of skill differences is working memory capacity (e.g., Just & Carpenter, 1992), such that better readers have more capacity and thus are able to process more information. However, there is only correlational evidence in favor of this notion, and it has not played a large role in comprehension theories (McNamara, de Vega, & O'Reilly, 2007; McNamara & Scott, 2001). A third is word knowledge (e.g., Chiesi, Spilich, & Voss, 1979). However, word knowledge is highly related to domain and world knowledge, which is a construct that is separable from comprehension skill (Perfetti, 1988). A fourth explanation is that better comprehenders differ in their use of long-term working memory (Ericsson & Kintsch, 1995). Accordingly, long-term working memory allows faster access to familiar information, and more-skilled comprehenders more effectively use long-term working memory. Though viable, some problems with this account are that long-term working memory is conflated with both prior knowledge and the use of reading strategies.

Thus, while various explanations and mechanisms have been proposed to account for differences in skill, including suppression, working memory, knowledge, and long-term working memory, it seems evident that more work needs to be done to account for skill differences within the context of comprehension models. Likewise, individual differences in general have been relatively ignored within comprehension models. More attention needs to be paid to how the assumptions underlying models of comprehension vary by reader, text, and context. We suspect that if such an approach were adopted earlier in the literature, arguments on whether readers do or do not generate this or that inference would have ended long ago, because these issues quite clearly vary as a function of the focus of the researcher in terms of the quadrants displayed in Figure 1. Endeavors to further investigate these factors and how they interact should lead to better understandings of how and when different processes emphasized in comprehension models are more or less likely to be evident.

5.7. Alternative Modes of Communication

The focus of these comprehension models has largely been on the comprehension of text presented in the written form. Most theorists assume that their models' assumptions largely extend to the comprehension of verbal discourse, and at least one model (i.e., the Structure-Building model) assumes that the assumptions extend to comprehension of information regardless of modality (verbal and visual). However, none of the models have in a detailed manner described differences between modalities, nor have they explained the integration of modalities.

One area ignored thus far by comprehension models is the effects of gestures. This is not to say that there is not research on the effects of gestures on comprehension (Cutica & Bucciarelli, 2008; Lozano & Tversky, 2006). However, thus far, these issues have not been incorporated within comprehension models. Similarly, issues surrounding text–picture integration and multimedia comprehension have been largely ignored by comprehension model theorists. This is partly an issue of the complexity of specifying a model of *text* comprehension, let alone comprehension of all modalities. In the case of implemented models, it also stems from the constraints imposed from programming issues. That is, how to depict a picture, graphic, or gesture computationally has not yet been solved. Additionally, the lack of integration of multimedia into comprehension models stems from a need for more, and better, research in these areas. Unfortunately, researchers who have investigated text–picture integration issues have concentrated largely on issues regarding the picture (and not the text) and on working memory constraints related to human factors issues, rather than on the cognitive processes related to text–picture integration. Moreover, the theoretical perspectives that have driven text–picture integration research have been largely based on outdated information processing theories and have tended to be more descriptive than explanatory in focus (Chandler & Sweller, 1991; Mayer, 2006; cf. Schnotz, 2002). As a consequence, it is not obvious how current theories of text–picture integration will meld with theories of text comprehension, at least the ones described here. Developing a complete understanding of comprehension calls for more research that focuses on the nature of multimedia, multimedia processing, and cross-modality integration of information and that more fully takes into account the processes involved in reading as well as processing involved in picture comprehension. In sum, progress is needed from both text comprehension and text–picture integration theorists in developing more viable models to explain the cognitive processes involved in multimedia processing.

6. Concluding Remarks

Our purpose here has been to outline where the field of text and discourse needs to go in order to move toward a comprehensive model of comprehension. We have made three principal conclusions based on our analysis of the current models of comprehension. The first is the current models of comprehension are not necessarily contradictory, but rather cover different spectrums of comprehension processes. We depicted these spectrums using Figure 1, which conveys the range of comprehension as a function of the reader and the text. The second conclusion is that although the models have collectively done so, no one model adequately accounts for a wide variety of reading situations depicted in Figure 1. Our third conclusion is that the range of comprehension considered thus far in comprehension models is too limited. It is time to go beyond the four quadrants in Figure 1. A comprehensive model needs to include a wide variety of phenomena that have not been considered thus far. Here, we have discussed the need to account for reader differences and text differences. Also, we have argued that it would benefit comprehension models to include assumptions regarding lower-level features and processes. Finally, there is a wide spectrum of issues that have not yet been tackled by current models. These include higher-level pragmatic processes and comprehension beyond text and discourse, including multimedia processing.

A comprehensive model will only be viable if it can generate testable predictions and can be computationally implemented. Given these criteria, it would be prudent to propose a model that contains explicit assumptions and parameters associated with the entire set of dimensions discussed in the last section. A comprehensive model will potentially include all of the dimensions that we have listed in Tables 1 and 2. However, some dimensions should emerge from fundamental assumptions and mechanisms in the model. Additionally, one obvious conclusion from our review is that, although many of the dimensions may be important, our understanding of them is not at the point where they are ready to be implemented in a comprehensive model.

A theoretical model of comprehension that comprehensively accounts for the full range of comprehension processes should optimally cover the four quadrants in Figure 1 and it must cover the range of bottom-up (automatic) and top-down (effortful) comprehension processes. Clearly, there are situations where bottom-up processes will likely fail to lead to a deep level of comprehension that is consistent with the reader's goals. A comprehensive theory should be able to specify the conditions when bottom-up processes will and will not be sufficient for comprehension and when top-down processes are likely to operate.

We propose that the spectrum of comprehension processes that have been observed in research emerges from three basic cognitive processes: spreading activation (e.g., priming), unconscious retrieval (e.g., memory-based retrieval), and conscious processing (e.g., strategies, problem solving, reasoning). In turn, these three processes serve to activate information sources in the text (i.e., bridging inferences in Figure 2) and sources outside the text (e.g., elaborative inferences), though in different ways. Such a schematic accounts for a wide range of inferences including text-based and knowledge-based inferences and also accounts for the range of automaticity that has been observed in the literature. The extent to which readers engage in less automatic inferences and mapping processes is likely to be a function of both the success of those processes and readers' goals and motivation.

A comprehensive model needs to also account for differences that occur as a function of genre. Reading processes, and in particular those involved in coherence building, differ as a function of text genre. Whereas the construction of the mental model of the text will rely primarily on event and causal elements within a narrative text, it relies more on referential (and causal) elements in expository text (particularly science text). Accounting for effects of genre within a model cannot be achieved simply by having a "genre" parameter because that would assume a genre detection homunculus and such an approach ignores mixed genres (which predominate).

The bottom line is that a comprehension model cannot be divorced from the text itself. It must take into consideration the text features, and how those text features guide how the reader processes the information in the text. For example, there are features of text that are more narrative-like, features that are more history-like, and features that are more science-like, and so on (e.g., Dempsey, McCarthy, & McNamara, 2007; Duran, McCarthy, Graesser, & McNamara, 2007; McNamara et al., 2008). Readers can detect these features very quickly in text, within about 3–7 words of the first sentence of the text (McCarthy, Myers, Briner, Graesser, & McNamara, 2009). In addition, the words themselves contain a host of other cues to the reader, driving expectations (e.g., through priming) on what words are likely to follow within a sentence and which ones are not (e.g., Elman, 2009). It is clear to us that although lower-level features have been for the most part ignored by comprehension researchers, without great consequence to the success of the models, this is largely because most of the models have centered on one type of text or another. A model that modulates processing as a function of genre (e.g., making links between verbs and nouns) will have to be sensitive to the characteristics of the text—just as the reader is. This will likely require a more complex connectionist architecture than what has been implemented thus far by comprehension theorists.

At the same time, the model also needs to go beyond the word. There is substantial evidence that readers derive meaningful idea units (i.e., propositions) when reading. Comprehension involves deriving larger units of meaning from the explicit text and inference processes and establishing relationships between them. As such, the simple solution of using the word as the unit of processing is not optimal. One question is whether the process of deriving the propositional unit can emerge from lower-level processes in the model. In either case, the role of idea units in comprehension cannot be ignored.

Just as the model cannot be divorced from the text, it cannot ignore the reader. What the reader brings to the situation—the ability or tendency to generate inferences, knowledge of words, knowledge of strategies, reasoning ability, knowledge of the domain, motivation, goals, and so on. These factors are important to consider and need to be included in a comprehensive model. One approach to this objective that we suggest avoiding is including mechanisms and parameters that simulate the effects of reader characteristics descriptively, but do little to explain what cognitive processes the readers are using and why they affect processing in the way that they do. Likewise, the model should account for conscious thoughts and decisions made while reading: strategies, reasoning, explanation, and so on. However, effortful, deliberate behaviors are not easily simulated in connectionist architectures. As discussed in Section 5, it is not clear where the solution lies to this problem, but it will likely require a hybrid architecture that lays a symbolic (e.g., production rule) system on top of a connectionist architecture.

Finally, we believe that more work needs to be done to understand comprehension in different modes and multimedia processing before a model can be developed that captures those processes. One possibility, however, is that those processes that are inherent to reading text generalize to the processing of all media (e.g., Gernsbacher & Faust, 1991). As such, working to build a more comprehensive model may bring us closer to accounting for comprehension regardless of medium. However, we reserve some pessimism on this point, particularly if the model includes both lower-level and higher-level processes.

The task that awaits the field of text and discourse to develop a comprehensive model of comprehension is daunting. First, researchers need to seriously reconsider and expand beyond the modeling approaches that have been used thus far in the comprehension literature. Second, a significant challenge will be to develop a model that not only accounts for the host of simple effects, but also accounts for the dependencies and interactions, particularly between characteristics of the text and the reader (i.e., that lie in the third and fourth dimensions of Figure 1). Despite these challenges, the time is clearly ripe for researchers and theorists to begin to think about comprehension more globally, across a range of tasks, readers, and reading situations.

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