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In a Word: ERPs Reveal Important Lexical Variables for Visual Word Processing

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Words are a language system's building blocks, making the apprehension and recognition of words one of the most fundamental language skills. Because words encapsulate different kinds of information, successful comprehension involves bringing online and integrating a number of diverse processes, such as analyzing the physical features of the incoming string, retrieving meaning representations and grammatical usages, and, eventually, relating the appropriate meaning and grammatical function to the larger discourse context. Given the complexity of these interwoven processes and their critical role in language comprehension, it is not surprising that word processing has been one of the most intensively studied topics in psycholinguistics.

In the psycholinguistic literature, a number of lexical features – including frequency, word class, concreteness, and ambiguity, among others – have been recognized for their robust influences on the process of recognizing words. Although such variables are often treated as independent and unitary, in this chapter we will review research using electrophysiological methods that expands this view by showing that some classic lexical effects documented in uni-dimensional behavioral measurements like response time or accuracy actually consist of multiple sub-effects. In particular, this body of work suggests that individual lexical features impact multiple aspects of the temporally distributed process of word recognition. Furthermore, these features are not independent dimensions, as they importantly modulate one another's influences.

The measurement of brain electrophysiology offers an importantly different perspective on word recognition because it provides a temporally precise, continuous, and multidimensional view of cognitive and neural processing. Event-related

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potentials (ERPs) measure brain electrical activity (derived from the continuous electroencephalogram or EEG) that is time-locked to a particular sensory, cognitive, or motor event (Fabiani, Gratton, & Federmeier, 2007). Because they are a direct assessment of brain activity and can track that activity on a millisecond level, ERPs provide the opportunity to continuously monitor processing and to measure temporally transient effects. ERPs are also a multidimensional measure, indexing multiple features (including amplitude, latency, and distribution) of multiple components linked to different aspects of neurocognitive functioning. Thus, ERPs offer the opportunity to observe different types of effects that may not be distinguishable in behavioral measures and/or that may occur too quickly to be captured by most other methods (for more details on this method, see Kutas, Kiang, & Sweeney, Volume 2, Chapter 26).

In this chapter, we review four widely recognized lexical features in turn: lexical frequency, word class (with a focus on the noun/verb distinction), linguistic concreteness, and lexical semantic ambiguity. Within the discussion for each lexical feature, we first provide a brief overview of the relevant behavioral and eye-tracking literature, then relate these findings to ERP studies that reveal the multifaceted nature of the effect in question, and finally discuss how the sub-effects highlighted by ERP studies may be influenced by information from other lexical features or from the larger language context. Taken together, these studies highlight the multidimensionality of the organization of the mental lexicon. They also tend to align well with more interactive views of lexical processing, in suggesting that word recognition is a flexible and dynamic process that is sensitive to features within the lexical item itself as well as to information in the surrounding linguistic context.

Lexical Frequency

Word frequency refers to the probability of occurrence of a given word in a language and reflects the accumulated experience one is likely to have had with that word. To estimate the frequency of a word, most studies have relied on calculating the number of occurrences of a certain written word form in a published corpus (e.g., Francis & Kucera, 1982). Although these can sometimes be dissociated, the frequency of a given word form oftentimes highly correlates with the frequency of its referent concept.

Effects of frequency are well documented and, accordingly, frequency has gained a prominent place in various models of word recognition (e.g., Becker, 1980; Morton, 1969; Norris, 1986). Overall, it has been found that higher-frequency words are associated with a number of processing advantages. Relative to lower-frequency words, readers tend to spend less time gazing at higher-frequency words (Just & Carpenter, 1980; Rayner & Sereno, 1994), and higher-frequency words can be named more quickly (Schilling, Rayner, & Chumbley, 1998), responded to faster in lexical decision tasks (Rubenstein, Garfield, & Millikan, 1970), and identified with shorter exposures (Solomon & Howes, 1951).

In the ERP literature, frequency has been found to modulate electrical brain responses at multiple time points during the course of word recognition. Effects of lexical frequency (or of the frequency of letter combinations; e.g., bigram and trigram frequency) have sometimes been reported within the first 200 ms after word presentation (e.g., Bles, Alink, & Jansma, 2007; Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006; Proverbio, Vecchi, & Zani, 2004), as amplitude modulations of sensory evoked responses. Word frequency has also been shown to affect the latency of a left lateralized anterior negativity between 200 and 400 ms (frequency sensitive negativity, FSN, or lexical processing negativity, LPN; King & Kutas, 1998; Munte et al., 2001; Osterhout, Bersick, & McKinnon, 1997) and the amplitude of the N400 between about 250 and 550 ms (for example, Bentin, McCarthy, & Wood, 1985; Rugg, 1990; van Petten & Kutas, 1990). Consistent with the more general sensitivities of these components to physical or semantic aspects of word processing, these frequency effects have been demonstrated to be differentially modulated by information related to physical or semantic aspects of a word.

Early frequency effects

Several studies have noted early ERP effects of lexical frequency or of the frequency of letter combinations (e.g., bigram and trigram frequency). Proverbio et al. (2004), for example, measured responses to real words, pseudowords and nonwords as participants performed a phoneme monitoring task. The results showed that word frequency modulated the response of the central-parietal P150, with more positive responses to higher- than lower-frequency words. Interestingly, this frequency effect was NOT sensitive to the lexical status of the stimuli: P150 amplitudes did not differ between low-frequency real words and well-formed pseudowords. Similar results were found by Hauk and colleagues (2006), who used a regression approach to examine the effects of frequency along with word length, orthographic n-gram frequency, and lexicality. They reported frequency effects as early as 110 ms, with decreased amplitudes for higher-frequency words. Effects of other surface variables such as length and n-gram frequency were similarly early, whereas the lexicality effect started at around 160 ms.

These early effects tend to be less robust and more variable across studies compared to later frequency effects. When they occur, they are usually associated with aspects of the brain response that are common to stimulus types other than words and that have been closely linked to sensory analysis and attention. For example, the P150 is elicited by images resembling any well-learned visual category and is particularly prominent for faces (Schendan, Ganis, & Kutas, 1998). Furthermore, the fact that these responses are typically similar for words and pseudowords suggests that they reflect some aspect of perceptual fluency driven by readers' experience with orthographic patterns in their language rather than by lexical frequency per se.

Frequency sensitive negativity (FSN)

Another lexical frequency effect has been observed in a slightly later time window over anterior electrode sites. Osterhout and colleagues (1997), looking at the response to words embedded in congruent or randomized prose passages, found an early negativity immediately followed the Nl-P2 complex that was sensitive to frequency, with higher-frequency words eliciting an earlier peaking negativity. This frequency effect was shown to be insensitive to the semantic congruency of the passage in which the words were embedded, but was found to interact with another physical feature of words, namely length: for words presented in both coherent text and randomized prose, the negativity's peak latency was negatively correlated with word frequency but positively correlated with length. Interactions between word frequency and word length on early effects have also been reported in other studies (Assadollahi & Pulvermüller, 2003).

A similar negativity (termed the frequency sensitive negativity, FSN, or lexical processing negativity, LPN) was also examined in King and Kutas (1998). With words presented in normal sentence contexts, King and Kutas observed a frontally distributed negativity whose peak latency varied as a function of lexical frequency, ranging between 280 and 340 ms postword onset. To isolate this early negativity from temporally overlapping slow potentials, King and Kutas obtained peak latencies from high-pass filtered ERPs. Regressions showed a negative linear correlation between the latency of the FSN and normalized word frequency, with high-frequency words (>10,000 per million) peaking at around 280 ms postword onset, medium-frequency words (~500 per million) at around 310 ms, and low-frequency words (<10 per million) at around 340 ms. King and Kutas found that after high-pass filtering, this negativity was not modulated by word length. However, similar to what was found in Osterhout et al. (1997), this high-pass filtered negativity was insensitive to higher-order word properties, such as the open/closed word class distinction (see Munte et al., 2001, for similar findings). Thus, effects of frequency within the first 300 or so milliseconds of word processing, although sometimes found to interact with other physical features of a word, have been largely shown to be separable from lexical class differences (e.g., open vs. closed class words) and syntactic/semantic processing.

N400 frequency effect

Various studies have found that the amplitude of the N400 is smaller in response to high- than low-frequency words (e.g., Rugg, 1990; Smith & Halgren, 1987; van Petten & Kutas, 1990), a pattern that suggests that more experience with a given word form facilitates semantic access. However, this particular frequency effect has been shown to interact with a variety of other factors that influence the ease of semantic processing, including word repetition (Rugg, 1990), ordinal word position in semantically congruent sentences (van Petten, 1993; van Petten & Kutas, 1990, 1991), and the predictability of a word in its context (Dambacher, Kliegl, Hofmann, & Jacobs, 2006).

For example, although lower-frequency words occurring near the beginning of sentences elicit larger N400s compared to higher-frequency words, this effect diminishes quickly over the course of a semantically congruent sentence (van Petten, 1993; van Petten & Kutas, 1990, 1991). Indeed, the N400s elicited by lower- and higher-frequency words are no longer statistically distinguishable beyond the fifth word of congruent sentences (van Petten, 1993). The N400 frequency effect is also reduced or eliminated when semantic access is facilitated by repetition, both in word lists and in sentence contexts (Besson, Kutas, & van Petten, 1992; Rugg, 1990; Smith & Halgren, 1987). Interestingly, however, the N400 word frequency effect appears to be insensitive to syntactic constraints, as it persists throughout the course of word streams that maintain legal syntactic structure without providing coherent semantic information (van Petten, 1993; van Petten & Kutas, 1991). Thus, frequency continues to affect processing at stages in which word forms are being mapped onto meaning, but its import is diminished in the face of other factors that affect the accessibility of semantic information.

Summary

Taken together, these studies suggest that accumulated language experience, as indexed by word frequency, affects processing throughout word recognition. It facilitates word perception in a number of ways, as indexed by changes in the amplitude of sensory-related components such as the P150, as well as reductions in the latency of the FSN. It also seems to be one of many factors that can ease semantic access, as indexed by N400 amplitude reductions.

Noun/Verb Word Class Distinction

Different kinds of words play different kinds of roles in language, making syntactic word class (e.g. nouns, verbs, adjectives, etc.) a critical factor for word processing. In particular, among content words, the distinction between nouns and verbs has been intensively studied and has been shown to play out in important ways in a variety of language and memory processes, including children's early lexical development (Gentner, 1982), memory performance (Reynolds & Flagg, 1976), and patterns of language deficits (McCarthy & Warrington, 1985; Miceli, Silveri, Nocentini, & Caramazza, 1988; Myerson & Goodglass, 1972).

In general, nouns and verbs differ along various dimensions, including average frequency, age of acquisition, lexical neighborhood density, number of semantic associates, and mutability of meanings (Gentner, 1981; Szekely et al., 2005). Much research has been devoted to singling out a critical dimension to account for the behavioral differences elicited by the two word classes. Some work has focused on the grammatical characteristics of these two word classes, such as the pivotal role of verbs for sentence construction (Berndt, Haendiges, Mitchum, & Sandson, 1997; Saffran, Schwartz, & Marin, 1980; Shapiro, Zurif, & Grimshaw, 1987) or the heavier morphological loading of verbs (Longe, Randall, Stamatakis, & Tyler, 2007). Other work has highlighted the differences in the semantic features associated with prototypical nouns and verbs, arguing that nouns and verbs tend to differ in their conceptual complexity, their degree of concreteness (Berndt et al., 1997; Williams & Canter, 1987), or their perceptual and functional/associative features (Bird, Howard, & Franklin, 2000; Marshall, Pring, Chiat, & Robson, 1996). All of these factors may well be important, and, indeed, noun/verb word class effects in behavior may be a composite manifestation of multiple kinds of processing differences.

For example, in a series of ERP studies, we have examined the processing of nouns and verbs in syntactically well-specified contexts (Federmeier, Segal, Lombrozo, & Kutas, 2000; Lee & Federmeier, 2006). To avoid potential limitations in generalizing to word class differences from more restricted subtypes of words (e.g., action verbs vs. object nouns), these studies included a wide range of nouns and verbs (including concrete and abstract nouns as well as action and nonaction verbs) matched for important lexical features and amount of preceding context. In light of the prevalence of word class ambiguity and the modulations of noun/verb effects by word class ambiguity that have been documented in the lesion literature (Jonkers & Bastiaanse, 1998; Kemmerer & Tranel, 2000), word class ambiguous words were treated as a separate category. Thus, effects could be assessed specifically for words that are exclusively or predominantly used as either nouns or verbs (e.g., word class unambiguous nouns like “beer” and word class unambiguous verbs like “eat”), and these could be compared with effects on word class ambiguous words used as nouns or verbs (e.g., “to drink” vs. “the drink”). Word class was cued by sentential (e.g., “Jane wanted to/the . . .”; Federmeier et al., 2000) or phrasal (e.g., “to/the . . .”; Lee & Federmeier, 2006) contexts that also served to specify the grammatical category for the ambiguous words. The results of these studies revealed two major noun/verb effects.

N400 word class effect

For both ambiguous and unambiguous words, nouns elicited more negative N400 responses (between 250 and 450 ms over central/posterior sites) than did verbs (Federmeier et al., 2000; Lee & Federmeier, 2006); see Figure 10.1. This is consistent with N400 response differences observed between nouns and verbs occurring in natural short passages (Osterhout et al., 1997) as well as for pairs of nouns and verbs in a lexical decision task (Rosler, Streb, & Haan, 2001). The fact that class ambiguous words also showed this pattern is in line with previous findings showing that, in the presence of disambiguating syntactic information, the

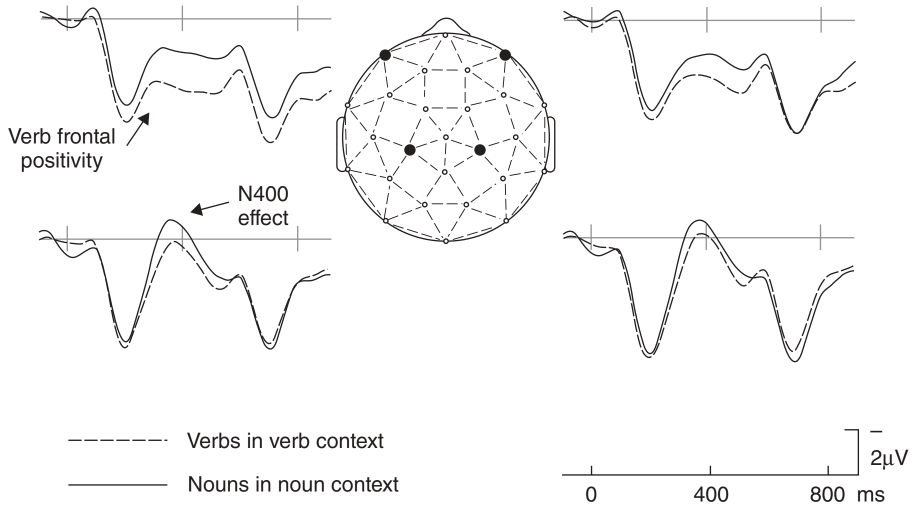

Figure 10.1 Noun/verb word class effects for word class unambiguous items. For this and all subsequent figures, data are shown at a subset of representative electrode sites indicated by enlarged circles on the head diagram. In the anterior region, verbs used in a verb-predicting context elicited an enhanced frontal positivity (200–400 ms post-stimulus-onset) relative to nouns used in a noun-predicting context. In the central/posterior region, nouns elicit more negative amplitudes than verbs on the N400 component. Data reported in Federmeier et al. (2000).

processing of these words tends to align with whatever word class the context indicates (e.g., Brown, Lehmann, & Marsh, 1980; Caramazza & Hillis, 1991). Overall, the fact that these noun/verb effects are seen in the form of amplitude – but *not* topographic (Gomes, Ritter, Tartter, Vaughan, & Rosen, 1997; Khader, Scherag, Streb, & Rösler, 2003) – shifts on the N400, a component elicited by all open class words, suggests that at this stage processing differences between nouns and verbs are quantitative rather than qualitative in nature, perhaps reflecting the number or type of semantic features associated with these word classes (or, in the case of ambiguous words, called up in response to the same word form when it is used as a noun or a verb).

Frontal positivity effect

In addition to quantitative processing differences on the N400, a frontally distributed positivity in response to verbs was evident between 200 and 400 ms post-stimulus-onset (Federmeier et al., 2000; Lee & Federmeier, 2006); see Figure 10.1. Unlike the effect pattern on the N400, this frontal positivity was seen only for word class unambiguous verbs and not for ambiguous words used as verbs (i.e., "Jane wanted to *drink* . . ." did not elicit this effect). Furthermore, the effect was seen only when the word class unambiguous verbs were in grammatically appropriate, verb-predicting contexts; the same lexical items did not elicit this effect when used in syntactically anomalous contexts, such as "Tom liked the *eat* . . .". The results thus extended previous observations of verb-specific frontal positivities with subsets of nouns and verbs (Dehaene, 1995: action verbs vs. animal names and proper names; Preissl, Pulvermüller, Lutzenberger, & Birbaumer, 1995: concrete nouns vs. action verbs) and further revealed that this processing difference reflects both the long-term and immediate syntactic environment in which a word occurs.

Summary

Together, these results suggest that the distinction between nouns and verbs encompasses a constellation of linguistic features and functions, which trigger different patterns of neurological responses over the course of word recognition. Behavioral processing differences are thus likely to arise from multiple sources, including both differences in the amount or type of semantic information accessed from nouns and verbs, as reflected by the N400 word class effect, and differences in the grammatical functions that these words can play and are playing within a particular context, as indicated by the frontal positivity to unambiguous verbs.

Linguistic Concreteness

Linguistic concreteness – i.e., the extent to which an expression describes a concept that can be perceived by the senses – has also been shown to have robust effects on language processing, in addition to various other cognitive processes such as free recall, recognition memory, and paired-associate learning (see the review by Paivio, Yuille, & Madigan, 1968). With respect to language processing, it has been found that concrete words are responded to more quickly in lexical decision tasks (Schwanenflugel, Harnishfeger, & Stowe, 1988) and are read aloud with higher accuracy and fewer semantic errors by deep dyslexic patients (Gerhand & Barry, 2000). The benefits of linguistic concreteness are also seen at the sentence processing level: concrete sentences are comprehended more quickly and accurately than are abstract sentences (Haberlandt & Graesser, 1985; Schwanenflugel & Shoben, 1983) and are responded to faster in tasks involving judging meaningfulness (Holmes & Langford, 1976) and truthfulness (Belmore, Yates, Bellack, Jones, & Rosenquist, 1982).

Several hypotheses have been put forward to account for the behavioral processing advantages observed for concrete words; among the more prominent of these are the dual-coding theory and the context availability theory. In his dual-coding theory, Paivio (1969, 1991) hypothesized that imagery is a critical determinant of concreteness-based processing differences. In particular, dual-coding theory posits that concrete words accrue a processing advantage because they can be accessed via both the imagery system and the verbal system (also used to store and process abstract words). In contrast, unitary semantic system accounts, such as the context availability theory (Schwanenflugel, 1991; Schwanenflugel et al., 1988) argue that the concreteness advantage comes from the richer availability of contextual information for concrete words. Support for this account comes from observations that the robust effects of concreteness seen for words presented in isolation or deprived of contextual information (e.g. in random sentential/paragraph contexts) are attenuated when words are repeated or are encountered in richer, semantically coherent contexts (Marschark, 1985; Paivio, Clark, & Khan, 1988; Schwanenflugel & Shoben, 1983).

Recent ERP studies, however, have instead uncovered data patterns suggestive of an account that combines elements of both views. Holcomb and colleagues (Holcomb, Kounios, Anderson, & West, 1999; Kounios & Holcomb, 1994; West & Holcomb, 2000) found that concrete words were associated with more negative-going potentials, beginning in the time window of the N400 component and continuing to up to 800 ms. Unlike the central/posterior focus for typical N400 effects, this concreteness-based difference was most pronounced over frontal scalp sites. The effect was more robust for tasks that tap more heavily into semantic processing (Kounios & Holcomb, 1994; West & Holcomb, 2000) but was strongly attenuated when concrete and abstract words were put into predictive sentence contexts (Holcomb et al., 1999) or were repeated (Kounios & Holcomb, 1994).

On the one hand, the scalp distributional differences between concrete and abstract words support dual-coding accounts in suggesting that different neural resources are involved in processing the two categories of words. On the other hand, however, the fact that the differences are observed in the time window of the N400 – a component that has been strongly linked to semantic processing (Kutas & Federmeier, 2000) – is suggestive that concreteness effects may be at least partially based on the richness of the words' semantic associations. Moreover, that the effect diminishes when semantic access is facilitated also makes clear that, as predicted by context availability theory, contextual manipulations can modulate concreteness-based processing differences. Based on their findings, therefore, Holcomb and colleagues have proposed the "context extended dual-coding hypothesis," which states that a complete account of concreteness effects must include not only multiple semantic codes for representing and processing the two different word types, to account for the topographic differences, but also a contextual component, to account for the context-based modulations (Holcomb et al., 1999).

The hypothesis that the impact of concreteness is mediated through multiple neurocognitive mechanisms is further corroborated by recent findings suggesting that the ERP concreteness effect itself is made up of dissociable subcomponents. In particular, the increased negativity to concrete words seems to reflect separable responses over central/posterior and frontal electrode sites, which are differentially sensitive to linguistic and task manipulations and have different neurophysiological sources.

Posterior concreteness effect

The posterior concreteness effect between 250 and 450 ms has been linked to modulations of the classical N400 component, with more negative amplitudes to concrete than to abstract words, when these words are encountered out of context. The effect is consistent across word classes, including nouns, verbs, and adjectives (Huang, Lee, & Federmeier, 2010; Lee & Federmeier, 2008), as well as words with different variations of lexical ambiguities, such as word class ambiguity (e.g. "to vote" vs. "the vote") and semantic ambiguity (e.g. "to watch" vs. "the watch"; Lee & Federmeier, 2008); see Figure 10.2. Given what is known about the functional sensitivity of the N400 (Federmeier & Laszlo, 2009), it seems likely that these processing differences arise from general semantic properties of words, such as the richness of the featural information that they evoke, and are mediated through basic mechanisms

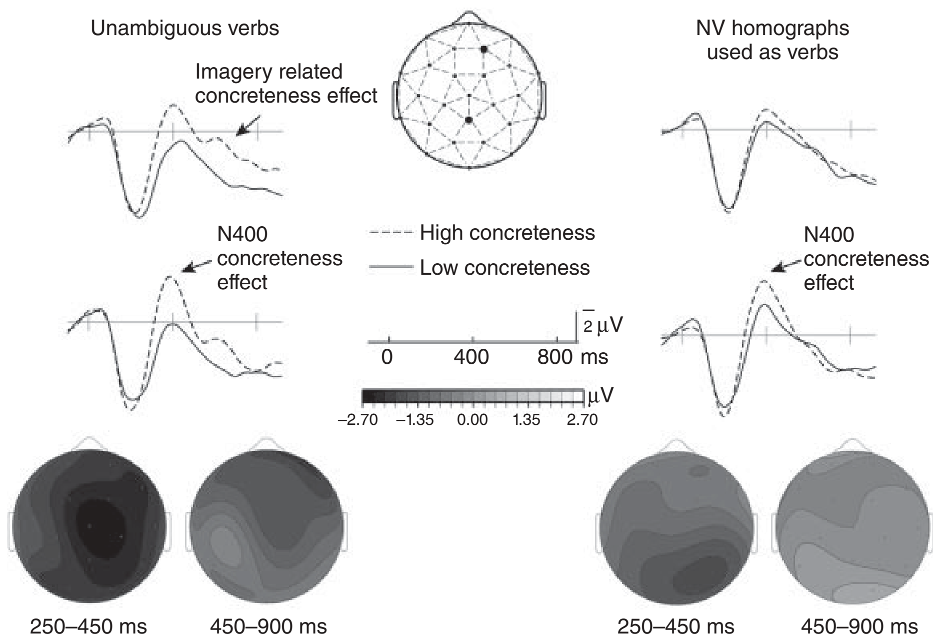

Figure 10.2 Concreteness effects for unambiguous verbs (left) and ambiguous words used as verbs (right). Unambiguous high concreteness verbs are more negative than low concreteness verbs. The negativity at central/posterior sites peaks around 400 ms (N400), whereas at frontal sites the difference due to concreteness extends to later parts of the epoch. Ambiguous words used as verbs show a similar concreteness effect over posterior but *not* frontal sites. The separability of the frontal and posterior effects is also shown in the isopotential voltage maps (bottom). For unambiguous verbs, the concreteness effect is widespread between 250 and 450 ms, and restricted to the anterior region between 450 and 900 ms. For ambiguous verbs, however, the effect is only apparent in the posterior region, in the earlier time window. Data reported in Lee & Federmeier (2008).

of semantic access. The hypothesis that highly concrete words may be associated with a richer set of semantic associations than less concrete words is supported by findings from a recurrent connectionist model (Plaut & Shallice, 1993) that defines concreteness as the number of associated semantic features and thereby successfully simulates the classic concreteness effect in deep dyslexia.

If the posterior concreteness effect seen to words out of context reflects differential effort involved in accessing words with many (concrete) as opposed to fewer (abstract) semantic features, then this effect should be attenuated in the presence of congruent context information that could serve to preactivate those features. Indeed, when concrete and abstract nouns are embedded in semantically constraining contexts, the posterior concreteness effect is attenuated or eradicated (Holcomb et al., 1999; Swaab, Baynes, & Knight, 2002). Furthermore, the same difference in richness of semantic feature information that makes concrete expressions harder to access out of context might render them more constraining contexts for words that follow them. Huang et al. (2010) showed that nouns preceded by concrete as opposed to abstract modifiers (e.g. "leather book" vs. "engaging book") elicit facilitated N400 responses (along with enhanced frontal P2 responses, a pattern that has been associated with increased contextual constraint; e.g., Wlotko & Federmeier, 2007). This N400 reduction was limited to cases in which the noun could be meaningfully integrated with the preceding adjectival context, suggesting that it was the activation of specific features of the nouns that was important. The effect was also observed only when processing of the critical nouns was biased toward the left hemisphere, consistent with views that only the left hemisphere uses context information to prepare for the processing of likely upcoming words (Federmeier, 2007).

These findings thus suggest that one difference between concrete and abstract expressions may be quantitative in nature: namely, the number of semantic features that each type of word routinely calls up. The consequences of this for processing manifest on the N400, reflecting brain activity associated with semantic access, and vary depending on whether these words are encountered in or out of context, or themselves serve as context for other words.

Frontal concreteness effect

As described earlier, concrete words encountered out of context elicit a widespread negativity relative to less concrete words. The concreteness-related negativity, however, is more long lasting over frontal scalp sites; for example, as seen in Figure 10.2, it is evident between 250 and 900 ms post-word-onset in Lee and Federmeier (2008). Similar frontally distributed negative potentials are also elicited in studies of mental imagery (taking into account differences in reference site; Farah, Weisberg, Monheit, & Peronnet, 1989). In addition, although this effect can arise without instructions or task demands that would bias participants to image (Huang et al., 2010), it has been shown to be enhanced by tasks that encourage mental imagery (West & Holcomb, 2000). Consequently, the frontal concreteness effect has been taken to reflect the mental simulation of sensory experience triggered by the meaning of a word, something that is perhaps exclusively available for concrete expressions.

Unlike the posterior concreteness effect, the frontal concreteness effect is not attenuated by supportive contextual information. Swaab et al. (2002) compared ERPs to highly imageable and less imageable words when these were preceded by related context (e.g., "pig" – "leopard"; "atom" – "molecule") or unrelated context (e.g., "wheat" – "slipper"; "pace" – "dispute"). Brain responses to the target (second) words were more negative over frontal electrode sites between 350 and 650 post-word-onset for highly imageable than less imageable words, irrespective of semantic relatedness. Whereas context does not eliminate this effect, it can modulate it – for example, in the case of words that can be understood with either a more concrete or a more abstract interpretation (e.g., the physical sense and the intellectual sense of the word "book"). In the Huang et al. (2010) study, polysemous nouns preceded by modifiers inducing a concrete reading (e.g., "hilly farm") elicited a frontal negativity (500–900 ms) compared to the same nouns preceded by modifiers inducing an abstract meaning (e.g., "productive farm"). Interestingly, this effect was only observed when processing was biased towards the right hemisphere, and only when the modifier could be meaningfully integrated with the noun. The fact that the frontal effect seems to arise from right hemisphere processing mechanisms is consistent with more general data linking the right hemisphere to imagery processes (e.g., Ehrlichman & Barrett, 1983; Kosslyn, 1987) and provides a strong dissociation between this effect and concreteness effects over posterior regions, which were associated with left-hemisphere-biased processing.

Thus, the elicitation of concrete conceptual information from a word or phrase seems to trigger the simulation of sensory experience (imagery), reflected in frontal negativity (see Bergen, Lindsay, Matlock, & Narayanan, 2007, for similar findings with behavioral measures). This predicts that, under certain circumstances, the frontal concreteness effect may be delayed or even suppressed if the prerequisite conceptual activation is difficult or prolonged – for example, if words are associated with multiple meanings, such that ambiguity needs to be resolved before imagery can take place. This prediction is born out in a study examining how concreteness interacts with semantic/syntactic ambiguity, comparing the processing of unambiguous words (e.g., "desk," "eat"), words with syntactic ambiguity only (e.g., "taste," which has related noun and verb senses), and words with both syntactic and semantic ambiguity (e.g., "register," which has unrelated noun and verb senses), in the context of a grammatical cue (e.g., "to" or "the") specifying the word class of the ambiguous words (Lee & Federmeier, 2008). The frontal concreteness effect was seen for all nouns regardless of ambiguity type (e.g., "the desk/plan/bat") and for verbs without semantic ambiguity (e.g., "to eat/plan"). Strikingly, however, this effect was *not* seen for syntactically and semantic ambiguous items used as verbs (e.g. "to register"); see Figure 10.2. Similar results have also been found in the behavioral literature. For example, Eviatar, Menn, and Zaidel (1990), using a lexical decision task, found that word class ambiguous verbs (with some degree of semantic ambiguity) failed to show the concreteness-based facilitation effect. Given that the meaning of verbs seems to be more context dependent, ambiguity resolution may be more difficult and/or take longer when a lexical item is used as a verb.

Summary

Collectively, the studies reviewed in this section suggest that linguistic concreteness has impacts on multiple aspects of neurocognitive processing – reflecting, for example, both the richness of associated semantic information as well as the possibility/efficacy of imagery processes. Whereas the central/posterior (N400) concreteness effect is a modulation of a process that is elicited by both concrete and abstract words and across word types, the frontal, imagery-related concreteness effect seems to involve an extra process that may be induced only by concrete items. Both effects are sensitive to the availability of semantic information, as modulated by context, albeit in different ways.

Lexical Semantic Ambiguity

Yet another factor that has been shown to greatly affect word processing is ambiguity. Ambiguity is a central feature of language at many processing levels; at the level of words, it is well documented that a single spelling or pronunciation is oftentimes associated with multiple meaning senses. In English, for example, 44% of a random sampling of words and 85% of a sample of high-frequency words had more than one meaning (Twilley, Dixon, Taylor, & Clark, 1994). Among lexically ambiguous words, some are associated with closely related meanings, such as "twist" and "hammer," whereas others are associated with unrelated meanings, such as "organ" and "watch." And, as demonstrated by these examples, alternative meanings can belong to the same or to different parts of speech. Depending on the relationship among the alternative meanings available for a particular word form, lexical ambiguity has been categorized as either polysemous, when meanings are related, or homonymous, when unrelated. Although ambiguity is graded, for words that are at one or the other end of this spectrum and thus are easy to classify, polysemy and homonymy have been shown to have differing effects on reading behaviors. Whereas related meanings have been shown to facilitate word recognition, unrelated meanings have been found to slow processing times (e.g., Rodd, Gaskell, & Marslen-Wilson, 2002).

Processing costs for homonymous words, in the form of delayed reaction times or increased gaze measures, have been found even in the presence of syntactically disambiguating information (Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; Tanenhaus, Leiman, & Seidenberg, 1979) or semantically biasing information, especially when context picks out nondominant interpretations (e.g., Duffy, Morris, & Rayner, 1988; Rayner, Pacht, & Duffy, 1994). Collectively, this literature suggests that multiple meanings are often activated even in the presence of contextual constraints.

Several theoretical accounts of the mechanisms of semantic ambiguity resolution have been put forward (e.g., Duffy, Kambe, & Rayner, 2001; Hogaboam & Perfetti, 1975; Paul, Kellas, Martin, & Clark, 1992; Rayner & Frazier, 1989). These theories vary in their assumptions about the autonomy of lexical activation and the general role of context in word recognition and language comprehension, but most, if not all, treat the processing costs that have been observed for ambiguous words as if they are unitary in nature and thus the same for ambiguous words encountered in different types of contextual environments. Whether different contextual information sources can critically alter how lexically ambiguous words are processed and what neural mechanisms are thus engaged is something that has rarely been discussed.

However, there are reasons to believe that different types of context information may affect lexical ambiguity resolution in different ways. First, semantic and syntactic contextual constraints differ in nature: syntactic constraints are oftentimes definitive but semantic constraints are more graded. For example, a sentence beginning "Paul liked the . . ." requires a noun phrase and thus would seem to rule out the verb use and meaning of an upcoming noun/verb (NV-) homograph such as "duck." In contrast, a sentence beginning "Mary searched in the bushes for the . . ." may favor the "tool" meaning of a subsequent ambiguous word "spade," but cannot rule out a continuation like ". . . spade, which had blown off the card table." On the other hand, syntactic constraints are likely to be considerably more general (e.g., requiring a noun but providing very little information about its features), whereas semantic constraints can be more specific. Semantic and syntactic information sources also differ in how they accrue across words and over time. Whereas semantic constraints build up incrementally over the course of a context, syntactic constraints seem more likely to operate locally. Semantically constraining contexts have been shown to lead to progressively faster word monitoring latencies and increasing N400 reduction over the course of sentences, but such accumulative effects were not found for syntactic contexts (e.g., Marslen-Wilson & Tyler, 1980; van Petten & Kutas, 1991). This difference between syntactic and semantic contextual constraints affects general word processing differently and thus could conceivably provide differential aids for lexical ambiguity resolution as well.

To examine this, we compared the influences of syntactic and semantic disambiguating information on ambiguity resolution for homographs whose meaning varies across word class (NV-homographs; Lee & Federmeier, 2009). We examined ERP responses to NV-homographs at the end of congruent sentences, which provide both a well-specified syntactic structure and constraining semantic information (e.g., "My grandpa said he hadn't played that game since he was a *kid*"), and embedded in syntactic prose, which offers identical syntactic cues but is semantically incoherent (e.g., "My board said he hadn't called that volcano since he was a *kid*"). The ERPs time-locked to the critical ambiguous words were then compared with those to matched unambiguous words in each type of context (e.g., "His

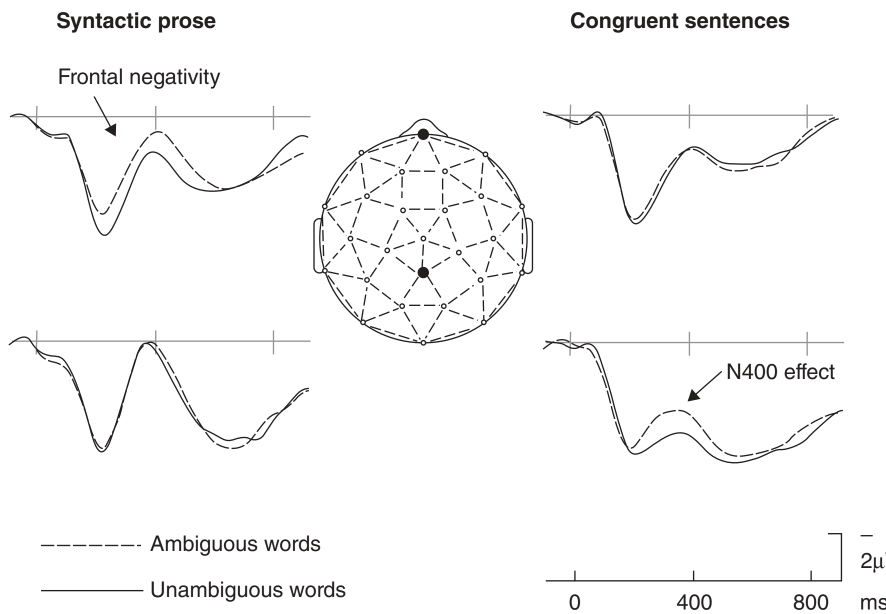

Figure 10.3 Ambiguity effects in congruent and syntactic prose sentences. In syntactic prose sentences (left), responses to ambiguous words (e.g. "the season/to season") are more negative than those to unambiguous words (e.g. "the logic/to eat") over frontal channels (200–700 ms). In congruent sentences (right), there is no enhanced frontal negativity. Instead, ambiguous words are more negative over central/posterior sites in the N400 time window (250–500 ms). Data reported in Lee & Federmeier (2009).

job at the store was his only source of *income*"; "His lot at the submarine was his big pet of *income*"). The results revealed qualitatively different processing consequences for homographs preceded by disambiguating syntactic versus semantic information.

Ambiguity resolution in the context of syntactic constraints

In the syntactic prose condition (left panel of Figure 10.3), NV-homographs elicited a prolonged frontal negativity (200–700 ms) relative to unambiguous words. This frontal effect replicates patterns in other studies, such as when NV-homographs are in midsentence positions of syntactically congruent but semantically unconstraining sentences (e.g., "Jeremy wanted to/the *watch* even though . . ."; Federmeier et al., 2000) or follow a single, syntactically constraining cue (e.g., "to/the watch"; Lee & Federmeier, 2006). The effect is not simply due to syntactic ambiguity, since word class ambiguous items whose meanings are very similar across their noun and verb senses (e.g., "drink") do not elicit this response (Lee & Federmeier, 2006). Similar effects have also been seen in cases that do not involve syntactic ambiguity, such as when there are multiple possible referents for a pronoun (van Berkum, Brown, Hagoort, & Zwitserlood, 2003; van Berkum, Hagoort, & Brown, 1999). Thus, the frontal negativity appears to be linked to processes of selecting among alternative referents, and is seen under conditions in which syntactic but *not* semantic constraints are available to aid with ambiguity resolution.

The idea that the frontal negativity indexes a controlled selection process receives support from several sources. Similar sustained frontal negativities have been observed in conjunction with working memory demands (King & Kutas, 1995) and the need to maintain and select among candidate items during recollection (Rugg, Allan, & Birch, 2000). Moreover, data from other imaging methods point to frontal lobe sources for selection-related brain activity. A number of hemodynamic imaging studies have reported frontal activation (for example, in the inferior frontal gyrus, either bilaterally or with a left hemisphere focus) associated with the resolution of lexical ambiguity (e.g., Mason & Just, 2007; Rodd, Davis, & Johnsrude, 2005; Zempleni, Renken, Hoeks, Hoogduin, & Stowe, 2007). In particular, Gennari, MacDonald, Postle, and Seidenberg (2007) used a design very similar to that of Lee and Federmeier (2006), with NV-homographs embedded in minimal syntactic phrases (e.g., "to/the bowl"), and found activations in the left inferior frontal gyrus that they linked to selection among competing semantic attributes. In turn, the conclusions of these hemodynamic imaging studies of ambiguity resolution are supported by more general results from the neuropsychological literature, which link frontal lobe damage to deficits in selecting relevant representations among competitors, including – but not limited to – tasks involving semantic ambiguity resolution (Metzler, 2001; Robinson, Blair, & Cipolotti, 1998; Thompson-Schill et al., 1998). This body of data thus suggests that selecting among alternative meanings of ambiguous words sometimes involves the recruitment of (possibly domain-general) frontal lobe control processes, and that this is a mechanism engaged when such words are encountered in circumstances that demand selection (i.e., in the presence of syntactic constraints) but that provide little semantic support.

Ambiguity resolution in the context of semantic constraints

The presence of constraining semantic context information greatly reduces the N400 to both ambiguous and unambiguous sentence final words (right panel of Figure 10.3). Strikingly, in the context of this general facilitation for word processing, there is no reliable evidence of frontal negativity for the NV-homographs. In other words, during the processing of a constraining, congruent sentence, the accumulated (pre)activation of semantic information seems to mitigate the need for recruitment of the kind of controlled selection mechanisms indexed by the frontal negativity.

However, this does not mean that ambiguous and unambiguous words are now processed identically. As can be seen in Figure 10.3, N400 responses to ambiguous words are less facilitated by context than are those to unambiguous words, despite careful matching of the two conditions for lexical properties and, critically, context-based predictability as indexed by cloze probability (Taylor, 1953). A follow-up experiment (Experiment 2 of Lee & Federmeier, 2009) showed that this ambiguity-related N400 difference was limited to cases in which the context picked out an ambiguous word's nondominant meaning (whereas responses to homographs in dominant-biased contexts fully converged with those to unambiguous words). This pattern is thus consistent with behavioral findings of processing costs for ambiguous words even in the presence of the disambiguating semantic information, when nondominant meanings are selected (Rayner et al., 1994; Duffy et al., 2001). What the ERP data make clear, however, is that the processing costs seen in these circumstances and those incurred when ambiguous words are processed in syntactically well-specified but semantically neutral contexts are qualitatively different.

In both cases, the processing costs seen in behavioral measures (e.g., increased response times) have typically been linked to competition between simultaneously activated meanings. For example, the reordered access model (see Duffy et al., 2001, for a review) assumes that, out of context, multiple meanings of ambiguous words become active, to a degree proportional to their meaning dominance. Context information can then "reorder" the meanings by changing their relative activation strengths. Strong activation, and hence rapid access, of the dominant meaning would be expected when high meaning frequency is buttressed by contextual support, allowing processing to approximate that for unambiguous words (as seen in Lee & Federmeier, 2009). However, subordinate-biased contexts will boost non-dominant meaning activation, making the activation levels of the two meanings more similar; thus, both when ambiguous words are encountered with little contextual support and when semantic context information is available but picks out a nondominant meaning, it is assumed that additional processes must be brought online to resolve the resultant competition.

The ERP data, however, tell a different story in suggesting that controlled selection mechanisms, linked to frontal brain activity, are necessary when semantic constraints are absent but *not* when nondominant meanings are picked out in the presence of semantically constraining context information. Although in the latter case there are residual processing differences between ambiguous and unambiguous words – which could have behavioral consequences – those ambiguity effects are of a qualitatively different nature. The larger N400 for ambiguous words in subordinate-biased contexts likely reflects a contextual mismatch created by residual activation of dominant meaning features. Importantly, however, it seems clear that the preactivation of subordinate-associated features from constraining semantic context information allows a sufficiently stable activation state to arise that the need for additional selection-related resources is mitigated, even in the face of residual automatic activation of dominant-associated meaning features. Thus, selection of a given sense of an ambiguous word need not entail fully selective access, in the form of activation limited to a single meaning.

Summary

The results across this pair of experiments are thus coherent with the behavioral literature in showing that neither syntactically nor semantically constraining context information can completely prevent the activation of alternative meanings of ambiguous words in all circumstances. Extending this literature, however, this set of data further suggests that similar behavioral processing costs (lengthened response times) for ambiguity resolution in different context types can arise from qualitatively different underlying neural mechanisms. When no biasing semantic constraints are available, arriving at the correct meaning of an ambiguous homograph (e.g., the one that fits a specified syntactic frame) involves the recruitment of (frontal lobe) selection-related resources, which manifest in the ERP signal in the form of a sustained frontal negativity. In contrast, when the context provides constraining semantic information, which facilitates semantic access, demands for these resources are reduced or eliminated. However, under these circumstances, contextually inappropriate meaning features may still become active to some extent, leading to reduced N400 facilitation for ambiguous as compared to unambiguous words, similar to patterns seen for unambiguous words that contain features that are unpredictable within a given context.

General Discussion

In this chapter, we reviewed electrophysiological research that highlights the multidimensional organization of the mental lexicon and the composite nature of word recognition. These studies show that a variety of attributes, including word frequency, word class, linguistic concreteness and lexico-semantic ambiguity, not only individually and jointly affect word recognition, but themselves consist of multiple sub-effects that impact multiple aspects of the temporally and spatially distributed processes of word recognition.

Recognizing a visual word involves mapping patterns of lines and curves onto stored knowledge of a given word form's associated semantic features, past experience with how that word form can be and is typically used in language, and the incrementally built representation of the current context in which the word form appears. It is thus not surprising that many different factors can render that mapping process easier or more difficult. For example, ease of semantic access, as indexed by the amplitude of the N400 component of the ERP, is affected by all of the variables discussed in the present chapter – not only by the richness and consistency of the semantic features associated with the word (concreteness and ambiguity), but also by whether the word form is being used as a noun or a verb, whether it is predictable in its context, and how often the connection between that letter string and its corresponding semantic features has been practiced, as in the case of higher-frequency words.

Indeed, the data make clear that the brain carefully tracks language experience on multiple levels, noting not only how often a given string has been processed (as indexed by frequency) but also specific aspects of how it has previously been used both syntactically and semantically. For example, if, in one's reading experience, a certain orthographic pattern has always been used as a verb, then verb-related information (as indexed by the verb frontal positivity) can be readily instantiated upon apprehending that word. However, if a given word form has previously been used as multiple word classes, this process is strikingly affected – even when context renders its current use unambiguous. Similarly, for words that have multiple discrete meaning senses, the more frequently a word is used in a context that supports a particular sense, the more dominant this sense will come to be. Later encounters, then, are highly shaped by this accumulated meaning dominance, such that, depending on the sense being picked out by the context, the recognition of an ambiguous word may be either indistinguishable from or more taxing than that for words with single meanings.

Furthermore, whereas some aspects of word processing seem fairly ubiquitous and are affected by a wide range of variables, as evidenced by patterns on the N400, other aspects of processing are more specific and brought online under particular circumstances. For example, the apprehension of concrete words is associated with imagery generation processes, which likely involve the automatic re-enactment of perceptual and motor states. However, a stable semantic state (one which seems more difficult to achieve for ambiguous words used as verbs), appears to be required before these processes can be initiated. In contrast, other processes are initiated by the *lack* of a stable semantic representation – such as those indexed by the frontal negativity associated with ambiguity, observed when semantic contextual constraints are unavailable to resolve the conflicting bottom-up information.

Given the diversity of the processes that could potentially be (and often are) involved in recognizing a word, a pivotal issue is how these processes are coordinated over time. The studies reviewed here suggest that although the involvement of some processes, such as imagery and controlled selection, is contingent on the (in)stability of the semantic state, the temporal onset of those effects nevertheless coincides with when information about a word's meaning features is just beginning to become available (as suggested by the timing of the N400). Thus, these processes seem to be initiated fairly rapidly and do not wait for meaning access to be completed but rather are carried out in parallel with it. Indeed, the data suggest that, perhaps due to the inherent time pressure created by the rapidity of normal language input, some processes simply do not occur if they are not initiated in time. Both the lack of a verb frontal positivity for word class ambiguous words and the lack of image-related negativity for doubly ambiguous words used in a verb context suggest that complications and/or delays in some aspects of word processing can lead to omissions of – or at least substantial delays in – other processes.

ERP data thus paint a picture of word recognition that is both more multifaceted and more dynamic than is sometimes assumed. We have shown that many lexical variables affect multiple aspects of word processing and that their effects are rarely independent of one another, or of the larger context in which a word occurs. In fact, although frequency, concreteness, word class, semantic ambiguity, and context effects seem very different linguistically, at least part of their influence on word recognition emerges from a common language processing mechanism – i.e., their respective effects on the N400, a component that seems to reflect a critical point in the temporally extended processing stream of word recognition, when many sources of information have simultaneous, interactive effects. More generally, the data show that what determines how lexical variables interact, what influence(s) they have, and even whether they have effects at all, is *time* . . . as successful and efficient word recognition requires that multifaceted and diverse information be brought together both over time and in time.

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