Action Field Theory:

The Roles of Memory and Action in Automaticity of Cognitive Control

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Abstract

Task-irrelevant features are processed even when people are fully aware of their undesired effects on task performance. This fact is exemplified by several types of interference effects in choice-reaction tasks, such as Stroop interference and the Simon effect. The observations are typically attributed to inextricable consequences of automatic cognitive processes involved in performing these tasks. However, evidence has accumulated suggesting that processes underlying these effects depend on one's intention to perform particular tasks, rather than being strictly automatic. Thus, there exists a paradox: the interference from task-irrelevant features presumes processes that are under intentional control. The present review attempts to resolve this paradox. I propose an integrated view of attentional control, *Action Field Theory*, which formulates principles that account for a range of phenomena concerning automatic control of human behavior.

Keywords: Selective attention; automaticity; Stroop task; Simon effect; action-based selection.

Introduction

People live in an inherently multidimensional environment and act on multivalent objects that afford several different actions in any given context. The utilities of these dimensions and object attributes change constantly depending on the task in which one is currently engaged. To optimize task performance, attention should be allocated across feature dimensions according to their utilities in the current task context. Understanding how people select appropriate stimulus features or dimensions has been of great interest in cognitive psychology (e.g., Allport, 1989; Logan, 2004; Treisman, 1988). *Selective attention* is a mechanism by which the cognitive system optimizes its processes to achieve a desired outcome more efficiently and effectively. Selective attention has traditionally been conceived of as a filtering process that blocks out irrelevant information from entering the system (Broadbent, 1958). Although people are remarkably capable of focusing on target information based on its physical properties (Cherry, 1953), early studies also showed that the filtering does not block all irrelevant information. For instance, people tend to notice information that has personal significance (e.g., own names; Moray, 1959), which could disrupt the task they are currently engaging. They may also mistakenly switch attending to a wrong source of information when its content matches the context of the currently attended information (Treisman, 1960), which could cause confusion and interference with the intended action. Nevertheless, the other side of the coin of these findings is an implication that processing of irrelevant information depends on a fixed set of factors, such as the contextual relevance or general pertinence of the information. Thus, task-irrelevant information is not processed arbitrarily. If so, the investigations into the cognitive principles behind processing of task-irrelevant information could help control or even eradicate its inadvertent consequences in one's action.

The goal of the present article is to review available evidence and synthesize a theoretical framework to understand the principles behind processing of task-irrelevant information. The framework delineates the mechanisms underlying selection across feature dimensions that give rise to automatic processing of task-irrelevant stimuli. To clarify the fundamental issues, this review will focus on the literatures concerning interference effects from task-irrelevant sources of information, such as Stroop interference and the Simon effect. Because comprehensive reviews of these phenomena already exist (e.g., Lu & Proctor, 1995; MacLeod, 1991; Proctor & Vu, 2006; Simon, 1990), the purpose of this review is not to list all past findings from the large literature in an exhaustive manner. Instead, the review will focus on findings that are most relevant to our efforts to synthesize a theoretical framework, *Action Field Theory*. The main issues are considered in light of existing theoretical approaches, and unresolved issues are identified. The principles derived from the theory are discussed in comparison to other prominent approaches in the field.

The Paradox

Experimental demonstrations of interference from task-irrelevant stimulus dimensions are abundant in the literature. A representative example is *Stroop interference*, the phenomenon in which naming the color of a word is considerably slowed if the word spells a color name incongruent with the to-be-named print color (Stroop, 1935). The *Simon effect* is another example that exhibits interference from task-irrelevant spatial attributes of stimuli (e.g., locations) that are incompatible with the action to be made in response to the stimuli (Simon & Rudell, 1967). These observations have been attributed to automatic processing of task-irrelevant stimuli (e.g., Kornblum et al., 1990; MacLeod, 1991; Posner & Snyder, 1976). However, researchers have expressed their doubts about such explanations (e.g., Bargh, 1989; Kahneman

& Treisman, 1986), and evidence has accumulated to support the idea that interference is not due to purely automatic processing of irrelevant stimuli (see, Moors & De Houwer, 2006, for a review). Studies in the last two decades are particularly suggestive of how automatic processes are dependent on intentional processes, on the one hand, and how intentional processes operate in an automatic fashion, on the other hand (see, e.g., Hommel, 2000b). Nevertheless, it is also true that interference from task-irrelevant information is robust and difficult to eliminate even if one is fully aware of the detrimental effects on performance. Thus, the paradox is that interference from automatic processing depends on intentionally controlled cognitive processes but is still difficult to eliminate intentionally. This motivated the development of the current theoretical framework. To illustrate the paradox in more detail, the following sections will review available evidence that indicates three key observations; (1) seemingly automatic processes depend on one's intention to perform a specific task, (2) intentional processes do operate in an automatic fashion, and (3) the main source of automaticity of cognitive processes is the actions set for a specific task. These observations serve as the primers for the forthcoming theoretical framework that provides a solution to the paradox in the present article.

The Primers for the Framework

Primer 1: Intentional Control of Automatic Processes

Psychological dimensions are analyzed separately for different 'features' of stimuli. This assumption is common in theories of visual attention (e.g., Duncan, 1984; Itti & Koch, 2000; Logan, 1996; Theeuwes, 1991; Treisman & Gelade, 1980; Wolfe, 1994), and evidence supporting this assumption is abundant (e.g., Fagioli et al., 2007; Mordkoff & Yantis, 1993; Mortier et al., 2005; Müller & Krummenacher, 2006; Treisman, 1986, 1988; Treisman & Gormican, 1988). For example, a target stimulus can be visually searched for more quickly when

the observers know in advance which stimulus dimension defines the target than when they do not (Treisman, 1988). Also, there is a cost of switching target-defining features across dimensions as compared to switching target-defining features within a dimension (Found & Müller, 1996). These results suggest that attention is dimensionally selective.

Selection across feature dimensions can be achieved by filtering out information that belongs to task-irrelevant dimensions. This selection mechanism apparently depends on a top-down or intentional process that allows pursuit of a specific goal. If this were not so, one would hardly be capable of, for example, naming the color of a word that denotes an incongruent color name (e.g., saying "red" for the word *BLUE* printed in red). However, it is also true that people have difficulty ignoring certain aspects of the environment, producing interference in task performance. Researchers have attributed such difficulty to automatic processing of task-irrelevant information (e.g., MacLeod, 1991; Posner & Snyder, 1976). Automatization is thought to occur when tasks are overlearned (e.g., Hasher & Zacks, 1979; LaBerge & Samuel, 1984), especially in an invariant context (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Once automatized, as the notion goes, processing of task-irrelevant information cannot be prevented, despite the fact that people may be fully aware of the interference that such information can cause to their performance.

Nonetheless, several researchers have challenged this view of automaticity on the ground that influences of task-irrelevant information are contextually dependent (e.g., Bargh, 1989; Logan, 1988; see Moors & De Houwer, 2006, for a review). For instance, exogenous attention capture, which is typically attributed to an automatic process (e.g., Jonides, 1981), has been shown to be contingent on the task-defined feature dimension (Folk et al., 1992). Likewise, studies suggest that even preattentive perceptual processes are subject to top-down control that

determines task-relevant stimulus dimensions (Müller & Krummenacher, 2006). Thus, there seems to be close interplay between processes that operate in a stimulus-driven fashion and those that require top-down control (Yamaguchi et al., 2018). The present section attempts to clarify factors involved in such interactions and draw a preliminary picture of the mechanisms underlying intentional control of automatic processes.

Reversing Automatic/Control Relations

Stroop interference has been used as a textbook example of an automatic process that operates independently of, or even against, one's intention to perform a specific task (see Logan, 1989; MacLeod, 1991, for reviews). A strong form of this automaticity view holds that there are fundamental differences between automatic and controlled processes (Posner & Snyder, 1975). An implication of this approach is that interference is unidirectional from automatic to controlled processes. This interference asymmetry is a robust finding in the Stroop task: Word-meaning interferes with color-naming, but word-color does not interfere with word-reading, which is known as the *Stroop asymmetry*. According to the automaticity account, word-reading is an over-practiced skill that has become automatized, whereas color-naming is not required very often in everyday activities and so requires deliberate control to initiate and complete the task. Thus, automatic word-reading is insensitive to contextual factors and cannot be interfered with by color-naming, whereas controlled color-naming is flexibly modulated by task contexts but can be interfered with by the automatic word-reading, resulting in the asymmetry of interference.

However, a pure form of automaticity has been challenged in Stroop studies (e.g., Besner, Stolz, & Boutilier, 1997; Kahneman & Treisman, 1986; MacLeod & Dunbar, 1988). Kahneman's contributions were particularly significant in this respect, showing that word-meaning does not interfere with color-naming if the word is printed in a color not included in the

set of to-be-named colors (Kahneman & Henik, 1981; also see Francolini & Egeth, 1980; Proctor, 1978) and that the influence of word-meaning is reduced, or diluted, when an additional neutral word is presented (Kahneman & Chajczyk, 1983). Moreover, Bauer and Besner (1997) reported an experiment in which one group of participants performed a two-alternative color-classification task (Stroop task), and another group performed a color-detection task (judge the presence or absence of 'red' stimulus). Importantly, both tasks involved the same stimulus configurations (congruent or incongruent color words), manual responses (pressing one or the other key), and S-R mappings (pressing one key to 'red' stimuli and the other key to 'green' stimuli), but Stroop interference occurred only for color classification but not for color detection. The findings imply that automatic processes involved in the Stroop task are sensitive to contextual factors.

Most strikingly, McClain (1983) demonstrated that the Stroop asymmetry can be reversed by changing how people respond to stimuli. In her study, participants were presented with the words 'HIGH" or "LOW", spoken in high or low pitch, and were to utter a relevant dimension (word meaning or voice pitch) or hum in a pitch corresponding to the relevant dimension. Interference from an incongruent word occurred when verbally reporting the stimulus pitch but not when humming that pitch. In contrast, interference from stimulus pitch occurred when humming the pitch indicated by a word but not when verbally reporting the word, reversing the direction of interference (also see Flowers et al., 1979; Lu & Proctor, 2001; O'Leary & Barber, 1993; Virzi & Egeth, 1985). This finding implies the importance of *stimulus-response compatibility* in Stroop interference: A task-irrelevant stimulus interferes with responding to a task-relevant stimulus when the task-irrelevant stimulus is more compatible with the required response than the task-relevant stimulus, but not vice versa. That is, there is nothing inherent in a

specific stimulus feature that makes it automatic. Stroop interference and the stimulus-response compatibility effect are typically considered to be distinct phenomena (e.g., Kornblum & Lee, 1995; Pratte, Rouder, Morey, & Feng, 2010), but the findings imply that these phenomena share the same underlying mechanisms. In other words, Stroop interference seems to be a special case of the stimulus-response compatibility effect that occurs based on task-irrelevant stimulus attributes, which is known as the *Simon effect* (Lu & Proctor, 1995).

Strategic Modulations of Automatic Processing

An early account of stimulus-response compatibility described the phenomenon in terms of the efficiency of translation process from stimulus to response (Fitts & Deininger, 1954; Fitts & Seeger, 1993). Fitts and Switzer (1962) suggested that when a stimulus is physically similar to a response, this process proceeds via a 'direct association' between the stimulus and the response, bypassing time-consuming response-selection processes. Consistent with this view, *dual-route models* of stimulus-response compatibility, which have been prominent from the 1990s to early 2000s, assume two routes for response selection (e.g., De Jong et al., 1994; Eimer et al., 1995; Kornblum et al., 1990; van Duren & Sanders, 1988). The dual-route accounts retain the traditional automaticity explanation of Stroop interference, in that, as the name indicates, a key feature is the assumption of two qualitatively distinct response-selection routes, one automatic and the other controlled. The accounts state that a stimulus automatically activates a spatially corresponding response, regardless of the relevance of that response in the current context, and interferes with processing of task-relevant information if the activated response is incompatible with the correct response required in that context. This illustrates that the dual-route accounts of stimulus-response compatibility follow the dichotomy between automatic and controlled processes implicated for Stroop interference, suggesting that processes may be strictly automatic

only when stimulus and response are highly compatible. However, evidence against the dual-route accounts of stimulus-response compatibility has also accumulated in the last decades.

For instance, Shaffer (1965) showed that the advantage of the compatible mapping can be eliminated when participants must select an S-R mapping on each trial (De Jong, 1994; Yamaguchi & Proctor, 2006), and, as in the Stroop task, the Simon effect depends on the relative frequency of compatible and incompatible trials (Hommel, 1994; Marble & Proctor, 2000; Toth et al., 1995). Similarly, the Simon effect is modulated according to task-instructions (Hedge & Marsh, 1975; Hommel, 1993) and task-demands (Koch & Prinz, 2005; Yamaguchi & Proctor, 2011b), and for tasks in which the location information is conveyed by words or arrow directions, the effect is reduced when an additional neutral stimulus is simultaneously displayed (Miles, Yamaguchi, & Proctor, 2009), suggesting that processing underlying the Simon effect is contextually sensitive and attentionally limited. These observations imply that automatic response activation is not an inevitable consequence of similarity or feature overlap between stimulus and response. Indeed, contemporary researchers seem to agree that the automatic process can be altered strategically (e.g., De Jong, 1995; Hommel, 2000a; Stürmer et al., 2002).

The exact mechanism that gives rise to strategic control of automatic processes is still subject to further research. One of the central questions in this issue is why task-irrelevant stimuli are encoded in the first place if automatic processes can be controlled when the stimuli are irrelevant to selecting the correct response or even activate an incorrect response. It is possible that all stimuli are processed and analyzed in parallel when they occur, regardless of their relevance to the task (Kornblum et al., 1990), which is consistent with late selection views of attention (Deutsch & Deutsch, 1965; Norman, 1968). It is also possible that encoding is selective with respect to which irrelevant stimuli should be processed according to the task goal,

as contemporary theories of visual attention propose (e.g., Müller & Krummenacher, 2006; Wolfe, 1994). O'Leary and Barber (1993) showed that response-irrelevant stimulus location interfered with reading a location word despite the fact that the spatial attribute is less compatible with naming a word than is the task-relevant word stimulus. This interference may happen because attending to the stimulus location is necessary to identify the word meaning and, thus, processing of location information is obligatory (e.g., Logan, 1998; Treisman & Gelade, 1980). This explanation is consistent with the *attention-shifting account* of the Simon effect (Stoffer, 1991; Umiltà & Liotti, 1987), according to which encoding of an irrelevant spatial feature is required in order to shift spatial attention toward the stimulus location. However, although this may be true, the attention-shifting account is severely limited in its scope and unable to explain phenomena outside of the spatial domain, such as the Simon effect based on color (Wühr & Biebl, 2009), numerosity (Wühr, Biebl, & Ansorge, 2008), duration (Grosjean & Mordkoff, 2001), or intensity (Romaiguère, Hasbroucq, Possamaï, & Seal, 1993). Critically in the present context, it cannot explain Stroop interference. At the same time, O'Leary and Barber (1993) also showed that although irrelevant word meaning did not produce interference when the relevant dimension was word location, it did produce interference when the task was modified to necessitate intentional processing of word meaning by requiring participants to identify the target stimulus (spatial word) from two simultaneously presented words.

The Role of Memory in Attentional Selection

Similarly to O'Leary and Barber (1993), Eimer and Schlaghecken (1998) demonstrated that subliminal priming of a response depended on whether the response matched the target stimulus. Their participants responded to a double-arrow (<< or >>) that occurred right after a prime stimulus. Although the participants were unable to perceive the primes according to a

separate recognition test, rapid initial activation of the response spatially compatible with the prime was observed in the lateralized readiness potential (LRP) measure of brain activity (which is assumed to reflect automatic activation of a response; e.g., Eimer, 1995) when the prime was also a double-arrow. Yet, the researchers found that the arrow-prime did not produce the automatic activation of a contralateral response when the targets were replaced with letters (LL or RR). These results suggest that not all stimuli are processed to the point where associated responses can be activated automatically. Instead, automatic response activation presumes intentional processes that decide what task dimensions are relevant to perform the task.

Ansorge and Wühr (2004) also showed that the Simon effect is produced based on one stimulus dimension but not on another, depending on how responses are defined in the task. In their study, participants started each trial by placing their index finger at the center key and moved it to one of two keys in response to the color of stimuli that appeared at one of four positions (left, right, top, and bottom). The Simon effect was obtained based on the vertical spatial dimension in a condition for which two response keys were located to the top-left and bottom-left of the center key. In contrast, the Simon effect was obtained based on the horizontal spatial dimension when response keys were located to the top-left and top-right of the center key. To explain these findings, Ansorge and Wühr (2004) proposed the *response-discrimination account* (also see Wühr & Ansorge, 2007), according to which the Simon effect occurs based only on stimulus features overlapping with response features that help discriminate between the alternative responses. They argued that pressing a key with either response set should have involved motor parameters for controlling the finger movements in the horizontal and vertical dimensions, but only the spatial dimension that was helpful for discriminating the alternative responses yielded a Simon effect.

Similar results were obtained in Wühr et al.'s (2008) experiments in which responses were varied in spatial location, numerosity (number of keypresses), or both. Again, the Simon effect occurred based only on the S-R correspondence in spatial location when the location of responses varied while the numerosity was held constant; it occurred based on the S-R correspondence in numerosity when the numerosity of responses varied while the response locations were held constant; and it occurred based on the S-R correspondences in both spatial location and numerosity when both factors varied between two alternative responses. These results are consistent with the notion that automatic processes presume intention to process certain task dimensions. The response-discrimination account emphasizes that, in order for a stimulus dimension to produce the Simon effect, alternative responses must be represented in working memory (WM) in terms of features in that dimension (Ansorge & Wühr, 2009). The importance of response representations may simply be due to the fact that automatic response activation is mediated by representations that are currently held in WM. Alternatively, there may be a more fundamental reason that response representations must be kept active in order for automatic response activation to occur.

Many recent studies in spatial attention underscore the importance of WM contents in exogenous attention orienting that is thought to be stimulus-driven or automatic. This was first demonstrated by Downing (2000), who had participants remember a human face at the beginning of each trial for a later recognition test. During the retention interval, participants performed a classification task for simple visual stimuli. The key manipulation was that two faces (the studied face and a novel face) were briefly presented on the left and right sides of the screen just before the target for the classification task occurred. Responses to the intervening visual task were faster when the target occurred at the location that had been occupied by the studied face than when it

occurred at the location that was occupied by a novel face. This result was interpreted as indicating that visual attention was captured by stimuli that matched the contents of WM. Downing showed that the effect was not obtained when the recognition test was eliminated in the procedure. These results have been replicated in subsequent studies (Olivers et al., 2006; Pratt & Hommel, 2003; Soto et al., 2008; Woodman & Luck, 2007), but researchers still disagree as to whether the memory-driven attention capture is purely automatic (Soto et al., 2008) or strategically driven (Downing & Dodds, 2004; Woodman & Luck, 2007). In particular, the strategic view suggests that the memory-driven attention capture is allowed when it (at least occasionally) benefits the goal attainment but not when it always disrupts performance (Woodman & Luck, 2007). And yet, these studies indicate that visual attention can be deployed to memory-matching stimuli in an automatic fashion when doing so can be beneficial to attain the actor's goal at least occasionally (Yamaguchi et al., 2018).

This memory-driven attention capture is typically explained with reference to the biased competition model of selective attention (Desimone, 1996; Desimone & Duncan, 1995). According to the model, an exemplar of the target object is retrieved into working memory as an attentional template, and a visual object that matches the template (Chelazzi et al., 1993), or is semantically associated with the template (Moores et al., 2003) is favored in competition for visual attention. Although the studies of memory-driven attention capture have focused on its role at a feature-level, Pan et al. (2009) demonstrated that capture can also occur at a dimension-level. Furthermore, there are studies that suggest a close link between Stroop interference and WM capacity (e.g., Kane & Engle, 2003). This link may be due to the fact that people with low WM capacity have more difficulty bringing the focus to the task-relevant attentional template than do those with high WM capacity. Kane and Engle termed the failure of attending to the

task-relevant stimulus features "goal neglect," which tends to occur to a greater degree in individuals who have lower WM capacity. A possible reason for this association between low WM capacity and the extent of goal neglect may be that response representations compete against goal (task-relevant stimulus) representations for limited resources, given that both representations are necessary to perform the task.

These findings in memory-driven attention capture suggest that selective encoding of task-irrelevant information, and the contingency of its influence on the task context, may be due to the need to keep certain memory representations highly active in WM to perform the assigned task. It follows that automatic processes presume an intentional act of control; that is, stimulus-driven processes have to be internally motivated. It is conceivable that the same mechanism is at work in the Simon task and Stroop task, which explains why the Simon effect and Stroop interference depend on the specific response requirements imposed by the tasks. In these tasks, response representations are highly active in memory and act as attention templates, so attention may be drawn to stimuli that share some attributes of the response representation in WM.

Primer 2: Automaticity of Voluntary Actions

Logan (1978) investigated the influence of memory load on a visual search task and tested whether load would interact with other experimental variables that were assumed to selectively influence distinct processing stages (encoding, response selection, response execution, etc.). Participants were required to remember a set of digits presented at the beginning of a trial for later recall, and performed a visual search task during the retention period or without the memory load. It was reasoned that if a processing stage is automatic, memory load would not interact with an experimental variable associated with the stage. These variables included the number of targets, stimulus quality, presence/absence of an exogenous attention cue, decision

type (yes/no), stimulus-response compatibility, and response mode (vocal/manual). The results indicated, however, that only the number of targets interacted with memory load.

Logan's (1978) interpretation of these results was that, although the task required attention (as memory load always had a main effect), component processing stages operated automatically and were free from attentional limitations. He stated,

> The components of the task seem automatic, but the task itself is not. Perhaps the stage structure of a task should be viewed as a temporary assembly of automatic, special-purpose processors organized by attention to deal with the task at hand. […] It may take attention, then, to *prepare* an appropriate sequence of structures and *maintain* it until a stimulus has appeared. (p. 57)

The last section showed evidence that automatic, stimulus-driven processes must be internally motivated. In contrast, Logan's proposal is that presumably controlled processes operate in an automatic fashion. Thus, two nominally different types of cognitive processes appear to operate in similar manners. The main objective of the present section is to establish how such interactions are possible.

Stimulus-Driven Response Activation via Task-Defined Rules

Automatic processes are not independent of one's intention to act, and intentional processes can operate in an automatic fashion. In the aforementioned study of Eimer and Schlaghecken (1998), for example, the LRP measures indicated rapid initial activation of responses even when the prime and target did not have explicit spatial features (i.e., when the prime and target were <> or ><) that would be shared with the required spatial responses. Such a demonstration provides evidence that stimulus-driven response activation is not restricted to conditions in which intrinsic S-R associations exist, but arbitrary S-R mappings can also yield

automatic activation. This observation is consistent with the occurrence of the flanker compatibility effect (Eriksen & Eriksen, 1974). In the flanker task, response competition arises between currently relevant and irrelevant S-R mappings, both of which are established by task instructions and cannot be attributed to pre-existing S-R associations. More recently, De Houwer (2004) showed that when participants were to respond to the color of stimuli with arbitrary utterances ("cole" or "cale"), responses were faster when the stimulus appeared at the location compatible with other spatial stimuli (arrows and location words) to which that response was assigned. That is, if a left-pointing arrow, the word "LEFT", and 'green' circle were mapped to the "cole" response, the response to the green circle was faster if it appeared on the left than if it appeared on the right (see De Houwer, 2003, for an analogous finding in an affective version of the Simon task). De Houwer et al. (2005) further provided evidence that, to yield this 'extrinsic' Simon effect, it is sufficient only to instruct participants about how to respond to the arrows and the words, despite the fact that these stimuli never actually occurred during the experiment. That is, even in absence of pre-existing S-R associations, an arbitrary association between response and other spatial stimuli induces a Simon-like effect, implying that stimulus-driven response activation depends on a purposeful task preparation.

Hommel (2000b) characterized stimulus-driven response activation via task-defined rules as a *prepared reflex*. As Logan (1978) proposed, the prepared-reflex notion suggests that the actor's intention does not appear to be situated somewhere between perception of stimulus and response programming, but it takes place at the very beginning of the task at which relevant task algorithms are prepared for future implementations (see also, Eder et al., 2010; Hommel, 2010). The role of intention may be more properly conceived of as establishment of a task plan (Logan, 2007; Miller et al., 1960), instead of implementations of mapping rules. Although relevant S-R

mappings must be maintained in an active state during the task, application of the S-R rules may be carried out without volitional processes once a task plan is established unless there is a need of altering the plan. This idea appears consistent with the findings of dual-task studies (e.g., Hommel, 1998; Logan & Schulkind, 2000; also see Way & Gottsdanker, 1968). These studies demonstrated that people respond to the first stimulus (R1) more quickly when the response is compatible with the response required for the second stimulus (R2), which is termed the *backward compatibility effect* (Hommel, 1998a).

Researchers generally agree that there is a bottleneck in the stream of cognitive processes that can operate one task at a time, although they disagree as to whether this bottleneck is due to a structural limitation (Pashler, 1994; Welford, 1952) or strategically created to optimize the task (Logan & Gordon, 2001; Meyer & Kieras, 1997). Researchers also agree that the bottleneck is located at the response-selection process in which executive control decides an appropriate response to a given stimulus. Hence, the selection of R2 cannot start until the selection of R1 has completed. However, the backward compatibility effect suggests that the R2 selection starts in parallel to the R1 selection. Logan and Schulkind (2000) varied the types of two tasks to be performed in the dual-task condition and found that the backward compatibility effect occurred only when the two tasks were of the same kind but not when they were of different kinds, indicating that the effect is obtained when the task does not need to be reprogrammed or switched. That is, the backward compatibility effect suggests that response selection can operate in parallel without executive control if the necessary control parameters have been prepared in advance. Consistent with these findings, Koch and Rumiati (2006) found that R2 was also faster when it was spatially compatible with S1 only if the spatial attribute of S1 was a task-relevant dimension (see also, Koch, 2009).

According to Logan and Gordon's (2001) model of dual-task performance, executive control is required to program parameters of subordinate systems that implement S-R mappings. Importantly, executive control is necessary when the parameters of the subordinate systems must be changed (e.g., from Task 1 to Task 2) but not when the parameters for the previous trial can be reused for the current trial. Once the parameters have been programmed, operations of the subordinate systems are autonomous. Hence, executive control is not necessarily involved in response selection on a trial-by-trial basis. In a more extreme case, executive control may be unnecessary even to change control parameters if they can be retrieved automatically. There is evidence that such automatic control of intentional act is possible.

Automaticity of Voluntary Act without WM

In dual-task situations, task-defined rules may be implemented automatically because multiple task rules must concurrently be maintained in WM. Thus, as the prepared-reflex notion suggests, the flanker and backward compatibility effects may be due to erroneous implementation of wrong S-R mappings. Yet evidence supports that actively maintaining task rules in WM may not be necessary for automatic implementation of task-defined rules. For instance, Yamaguchi and Proctor (2011a) had participants perform two-choice reaction tasks based on the color or shape of stimuli and examined the *response congruity effect* (faster responses when the color and shape are assigned to the same response than when they are assigned to different responses), analogous to the flanker compatibility effect. If concurrent maintenance of S-R rules is required for stimulus-driven response activation to occur, the influence should be eliminated when task uncertainty is excluded.

This prediction was tested in two ways. First, it was hypothesized that the influence of stimulus-driven response activation should decline as the interval between a task cue and

stimulus (cue-target interval, CTI) increases if concurrent maintenance of irrelevant S-R mappings is necessary. With the task procedure, cost of switching tasks (longer response times when the task performed on the preceding trial switches for the current trial than when it repeats) is found to dissipate over CTIs. This task-switching cost is thought to stem from relative activation of relevant and irrelevant task-sets (e.g., Allport et al., 1994; Rogers & Monsell, 1995; but see Logan & Bundesen, 2003; Mayr & Kleigle, 2003), which implies that the influence of irrelevant S-R mappings should also dissipate over CTIs. However, in the study, the switching cost declined but the congruity effect did not. Second, Yamaguchi and Proctor (2011a) separated two tasks into different blocks, assuming that irrelevant S-R mappings would no longer be actively maintained in WM because participants knew that the mappings would never be used in a given block. Consistent with this prediction, responses were much faster when tasks were blocked than when they were intermixed (even when the blocked condition was compared to task-repeat trials of the mixed condition), implying that irrelevant S-R mappings were unloaded from WM. Yet, the congruity effect persisted in the blocked condition. Taken together, these results suggested that the congruity effect was not due to irrelevant S-R mappings being held active in WM, implying that automatic implementation of task-defined rules does not depend on the content of WM alone.

Memory-Based Control of Thought and Action

The observations appear to be consistent with the *memory view* of automaticity (Logan, 1988). The traditional view of automatic processes, underlying the dual-route accounts of stimulus-response compatibility and the automaticity account of Stroop interference, is sometimes called the *modal view* because of its close association with the Donders-Sternberg-type model of information processing (Donders, 1868/1969; Sternberg, 1969b). The modal view

suggests that automatization involves a shift of processing modes through extensive training, without specifying the underlying processes responsible for the qualitative shift (Logan, 1992). Alternatively, the memory view states that processes are automatic if they depend on retrieval of past S-R episodes (Logan, 1988). This *instance theory* of automaticity diverges from the modal view, in that it proposes that automatic processes are not constrained by a set of characterizations that define the kind of processes in the modal view. Instead, the memory view argues that it is the underlying mechanism that determines whether performance is automatic or not.

An implication of the memory view is that automatic processes can occur without extensive training (Logan & Etherton, 1994; Zbrodoff, 1999). In fact, it predicts that automaticity can arise even after single encounters with particular S-R episodes or after the task is instructed without actually performing the task (Logan & Klapp, 1991). These predictions are consistent with the findings such as those of Waszak et al. (2003), where there was a larger cost of starting a new task if a stimulus had been encountered previously in a different task context even once, and those of the aforementioned studies that demonstrated the 'extrinsic' Simon effect (e.g., De Houwer et al., 2005) based only on instructions. There has been increasing emphasis on the role of memory retrieval in cognitive control. For instance, the Simon effect, Stroop interference, and the flanker effect are smaller in trials that immediately follow an incompatible trial as compared to trials that follow a compatible trial (e.g., Gratton et al., 1992; Notebaert et al., 2005; Stürmer et al., 2002). These sequential modulations have been interpreted as implying involvement of executive control that adjusts the cognitive system to resolve processing conflict (Botvinick et al., 2004; Gratton et al, 1992; MacLeod, 1991). According to this account, a processing route responsible for task-irrelevant information is suppressed when response conflict is detected, and this suppression carries over to the immediately following trial

(Stürmer et al., 2002). However, other studies have suggested that the sequential modulations are due to priming of a previous task episode (e.g., Hommel et al., 2004; Mayr et al., 2003).

Hommel et al. (2004) provided a detailed analysis of sequential modulations and showed that responses were faster in the Simon task either when both relevant and irrelevant stimuli repeated (complete repetition) or when both switched (complete alternation) than when only one of the stimulus attributes repeated (partial repetition). The Simon effect is large after a compatible trial because a subsequent compatible trial is a complete repetition or complete alternation, whereas an incompatible trial is a partial repetition. In contrast, the Simon effect is small after an incompatible trial because a subsequent compatible trial is a partial repetition, whereas an incompatible trial is a complete repetition or complete alternation. To account for the pattern of the Simon effect, Hommel et al. suggested that task-relevant and irrelevant features are integrated into a task episode, and there is a cost of unbinding these features when only one of them is repeated but not when all features repeat or alternate. This priming view emphasizes automatic retrieval of task episodes, which is also supported by other studies. For instance, Mayr et al. (2003) found that the sequential effect was task specific. They alternately administered two versions of the flanker stimuli (horizontally or vertically oriented) and showed that the reduction of the flanker effect at the current nth trial depended on the compatibility on trial $n - 2$ of the same stimulus type but not that on trial $n - 1$ of a different stimulus type. Spapé and Hommel (2008) also found similar stimulus-specific sequential modulations using female and male voices to present auditory Stroop stimuli. Wendt et al. (2006) and Fernandez-Duque and Knight (2008) further showed that the sequential modulations of the Stroop or Simon effect are not altered by the compatibility of an intervening flanker task. In addition, Fischer et al. (2010) intermixed dual- and single-task trials and found that sequential modulations of the Simon effect depended

on whether the previous trial was of the same trial type. These findings imply that sequential modulations of the Simon effect or Stroop interference are due to stimulus-driven retrieval of a task episode rather than stimulus-independent adaptation to conflicting stimuli.

The role of memory retrieval has also been demonstrated in the task-switching procedure, which is believed to involve highly controlled processes (e.g., Logan & Bundesen, 2003; Mayr & Kliegl, 2000; see Logan, 2009, for a review). As mentioned, task-switching cost has been attributed to residual activation of an irrelevant task-set (Allport et al., 1994) or intentional reconfiguration of the relevant task-set (Meiran, 1996; Rogers & Monsell, 1995). However, Mayr and Kleigl (2000) showed that task switching cost depends on memory-retrieval demands but not on task complexity or difficulty, questioning the attribution of task-switching cost to executive control. Logan and Bundesen (2003) and Mayr and Kleigl (2003) also showed that a major component of task-switching cost is due to switching of task-cues when the relevant task is explicitly cued in advance, thus implying that the cost reflects benefit of task-cue repetitions. Rogers and Monsell (1995) suggested that task-defined rules can be retrieved in a stimulus-driven manner. They reported that responses were generally faster when task-irrelevant stimuli were neutral with respect to response selection as compared to when they were compatible or incompatible with the task-relevant stimuli. Likewise, Arrington and Logan (2004; Arrington, 2008) proposed that a stimulus-driven retrieval process contributes to voluntary selection between alternative tasks, in that the probability of task repetition in their experiments depended on the availability of relevant stimuli. In a similar manner, Weaver and Arrington (2010) proposed that irrelevant memory items held in WM determine voluntary task selection. Therefore, at least when the tasks are as simple as selecting between a few (typically two) alternative responses, cognitive control can operate based on automatic retrieval of temporary S-

R associations.

A Unitary View of Memory and Attention

In the context of the present article, the memory view of automaticity raises an important challenge. Whereas the earlier sections highlighted evidence supporting involvement of intentional processes or goal-settings in operations of automatic processes, there is also evidence that automatic processes are independent of WM. From the view that WM is associated with executive control (e.g., Baddeley, 1992), the conclusions seem contradictory. However, the observations are reconciled in a unitary view of memory and attention (e.g., Anderson, 1983; Cowan, 1988).

As in the aforementioned study by Yamaguchi and Proctor (2011a), Meiran and Kessler (2008) examined the congruity effect in the task-switching paradigm and raised a paradox associated with the effect that mirrors the present issue. They pointed out that the congruity effect depends on task preparation, in that the effect is obtained even when task switching is expected but never occurs (Yehene et al., 2005). The congruity effect does not interact with concurrent memory load (Kiesel et al., 2007), suggesting that the effect does not depend on WM. To resolve the paradox, Meiran and Kessler suggested that the congruity effect stems from an "activated portion of LTM," the idea originating from a unitary view of memory that sees WM as a sub-region of the LTM (e.g., Anderson, 1983; Cantor & Engle, 1993; Cowan, 1988; Öztekin et al., 2010), not a structurally distinct component as popularly assumed (Atkinson & Shiffrin, 1971; Baddeley, 1992). Of particular importance in the context of the present issue is Cowan's (1988, 1995) framework: Whereas other unitary views suggest that the temporal storage is a portion of activated LTM and is limited in capacity, Cowan's framework further distinguishes the activated LTM into WM and short-term memory (STM). It proposes that STM is composed

of activated LTM, and WM is a sub-region of STM that is currently in attentional focus. From this view, the focus of attention can contain a limited number of items, whereas the region of STM can expand without a limit.

This unitary view is supported by several studies (e.g., Klapp et al., 1983; Oberauer, 2001). Of most relevance is Oberauer's study, in which he used a variation of Sternberg's (1969a) memory scan task. Participants were presented with two lists of memory items and were later cued to judge whether a probe was present in a target list while ignoring the other list. Responses were faster when the set size of the relevant or irrelevant item list was smaller. This set-size effect based on the relevant list increased, but the effect based on the irrelevant list decreased, as the interval between the study lists and the probe (i.e., CTI) increased. However, Oberauer also suggested that the influence of irrelevant list on task performance even after the set-size effect had ceased, because response time was generally longer to reject the probe when it was from the irrelevant list than when it was from neither list. This intrusion effect remained even with a 5-s CTI. Oberauer interpreted these results that the divergence between the set-size effects was due to a gradual shift of attentional focus toward the relevant list and away from the irrelevant list, but the irrelevant list remained in the activated region of LTM (i.e., STM), producing the persistent intrusion effect. Oberauer (2002) later proposed a further distinction between a region of immediate access, which can hold a limited number of items (e.g., 4 items), and the focus of attention, which can only hold a single item. This approach appears consistent with the findings that the congruity effect remained significant after irrelevant S-R mappings were unloaded from WM and that the effect was independent of CTI (Yamaguchi & Proctor, 2011a). That is, as suggested by Meiran and Kessler (2008), the congruity effect arises from the activated portion of LTM, rather than a capacity-limited focus of attention (WM). This

conclusion also explains the larger congruity effect in the mixed-task condition than in the

blocked-task condition (Yamaguchi & Proctor, 2011a), because activation of LTM assumedly

dissipates over time when it is not used for a period of time (Oberauer, 2005).

Intention and Automaticity in the Same Nest

From the memory view of automaticity (Logan, 1988), automatic processes are those that

operate based on retrieval of task episodes or instances. This conception fits the idea that WM is

a portion of LTM that is activated above a certain threshold (e.g., Anderson, 1983), which is

consistent with a filtering model of selective attention proposed by Treisman (1960). Moreover,

Cowan's (1988) distinction between STM and WM (focus of attention) provides an explanation

for the role of intention in automatic retrieval of task episodes. Several studies have

demonstrated automatic processes based only on instructions without actually administering the

task (e.g., De Houwer et al., 2005; Zbrodoff, 1999; Yehene et al., 2005) or after a single

encounter with the task (e.g., Waszak et al., 2003). These findings can be explained if task rules

or episodes remain active in LTM, without being active in WM. Conversely, other studies have

shown that automatic processes do not occur if task features that encourage intention to process

task-irrelevant information were excluded (e.g., Ansorge & Wühr, 2004; Eimer & Schlaghecken,

1998; Koch & Prinz, 2005; Yamaguchi & Proctor, 2011b). The observations are also consistent

with the framework in that relevant LTM becomes deactivated when such features are no longer

present in the task context. Thus, automatic processes require pre-activation of LTM

representations (STM), and they are retrieved when stimuli associated with the representations

are encoded into memory. On the other hand, controlled processes are those that operate by

shifting attentional focus in LTM (or the region of immediate access; Oberauer, 2002). Thus,

task-switching costs may be obtained because the attentional focus has to be shifted from one

place to another, though what is attended during this operation is still a matter of controversy (e.g., task rules vs. task cues; Logan & Bundesen, 2003).

This nested view of automatic and controlled processes appears radically different from typical explanations of interference phenomena such as the Simon effect and Stroop interference. These explanations rely on qualitative differences between automatic and controlled processes (e.g., Kornblum et al., 1990; Posner & Snyder, 1976), but the present interpretation suggests that these processes do not differ in their qualities. Instead, controlled and automatic processes differ only in the degree to which activation depends on the operations that must be implemented to accomplish the immediate goal. Note that the present emphasis differs from that of the view that degree of automaticity is simply a function of the amount of training (e.g., Dunbar & MacLeod, 1988; Hasher & Zacks, 1979), because the latter is silent as to the mechanism underlying automatic processes. The current view, which describes that mechanism, is supported by the recent findings reviewed in the previous sections.

The nested view of automatic and controlled processes also shares the core structural assumption of cognitive control with the hierarchical theory of skilled performance (Logan & Crump, 2011). According to the hierarchical theory, highly trained skills are controlled by nested control loops that have different processing units. For example, in skilled typewriting, lower-level control loops process smaller chunks (e.g., letters or individual keystrokes) and are embedded within a higher-level control loop that processes larger chunks (e.g., words). When they intend to type words, typists would implement the higher-level loop, but the operations of the lower-level loops are also triggered automatically without intending to type each letter because the lower-level loops are embedded within the higher-level loop. From this view, automatic and intentional processes are not separate routes of cognitive processes, but they are

part of a larger system in which both automatic and intentional processes are utilized in concert. It is, thus, misleading to consider automatic and intentional processes as qualitatively distinct processes. In fact, skilled typists can shift their attention from a higher-level loop to a lower-level loop, for example, when they are required to type unfamiliar words or when they type on an unfamiliar keyboard (e.g., Yamaguchi & Logan, 2014; Yamaguchi et al., 2017), which deteriorates their typing performance. The hierarchical structure of cognitive control allows skilled actors to perform a task without thinking about the details of the task (Logan, 2018), but it also allows them to think of the details if it is needed to optimize the performance outcomes (e.g., the accuracy of typing letters).

Primer 3: Action-Based Selection across Feature Dimensions

Empirical evidence showed that automaticity of cognitive processes involves intentional control (Hommel, 2000a, 2000b; Logan, 1989; Yamaguchi & Proctor, 2011b), whereas task-defined rules that should require intentional control of relevant operations can exhibit characteristics of automatic processes (Hommel, 1998; Logan & Etherton, 1994; Yamaguchi & Proctor, 2011a). These observations are readily accommodated by the nested model of automaticity and cognitive control (Cowan, 1988; Oberauer, 2001). Yet, this model does not explain why a complete elimination of interference is hardly ever achieved. One could experience that such elimination does not happen by performing the Stroop task. This is puzzling: If automatic processes are under the actor's control, interference from task-irrelevant stimuli should be eliminated easily when attempting to do so. Therefore, there is a missing piece in the framework that needs to explain why interference has to occur. This missing piece is the notion of action-based selection, which is the idea that features in the environment are selected for cognitive processing according to its relevance and resemblance to the actions being prepared

for a given task.

The Role of Action in Stimulus Encoding

Evidence supporting the notion of action-based selection has been provided in studies

using a variety of experimental paradigms, such as visual search (Bekkering & Neggers, 2002;

Hannus et al., 2005; Wykowska et al., 2009), target detection (Craighero et al., 1999; Fagioli et

al., 2007), and choice reactions (Hommel, 2007; Hommel & Schneider, 2002; Müsseler &

Hommel, 1997a). For instance, Bekkering and Neggers (2002) had participants look for a

rectangular target embedded among distractors that differed in color or orientation. They found

that initial saccades were made toward distractors that differed in orientation more frequently

when participants were asked to point to the target than when they were asked to grasp it. In

contrast, initial saccades were made toward distractors with different colors equally often for the

two types of response conditions. The researchers suggested that preparing to grasp enhanced

attention to the orientation because the stimulus feature dimension provides important

information regarding how the grasping action should be carried out. Likewise, in Fagioli et al.'s

(2007) study, participants were presented with a sequence of visual displays in which a circular

object moved in a regular fashion. Two types of display sequences were prepared. For one type,

the object trajectory deviated from the regular route on one of the displays, and for the other type,

the size of the object on one display deviated from that on others. Participants' goal was to detect

either type of deviation and respond by reaching a button with the index finger or grasping an

object with the hand. A location deviation was responded to faster when the responses were

reaching than grasping, but a size deviation was responded to faster when responses were

grasping than reaching. Wykowska et al. (2009) used a visual search task that required a

grasping or reaching response and found that the target was detected quicker when it was defined

by its size if the response was grasping an object rather than reaching the object, whereas the pattern was reversed when target was defined based on luminance. These results indicate that processing of stimuli is facilitated when the stimuli are closely related to the actions required to perform the task.

Enhancement of Stimulus Encoding by Response Preparation

The role of response preparation for enhancing stimulus encoding is further supported by Hommel and Schneider's (2002) study, in which detection of a target in a visual search task was found to be more accurate when the target location spatially corresponded to a response that was prepared for a preceding stimulus but that had not yet been executed when the search display appeared. Likewise, in Hommel's (1998) aforementioned dual-task study, the backward compatibility effect was found when R2 was compatible with S1. In this task variation, manual responses (R1) were made to the stimulus color (S1; green or red), and vocal responses (R2) were made to the stimulus shape (S2). The vocal responses were the utterances "green" and "red". R1 was faster when S1 was compatible with R2, suggesting that processing of S1 was facilitated. Such a finding is consistent with the notion of action-based selection.

Furthermore, in Verfaellie et al.'s (1988) Simon experiment, the correct response was signaled by the direction of arrows prior to onset of the imperative stimuli. This response precuing enhanced the Simon effect (also see Proctor et al., 1992; Proctor & Wang, 1997). The enhancement of the Simon effect may be due to preparation of a response increasing the activation of a spatial code associated with that response. Thus, a small but rapid increment of response activation by the presentation of a corresponding spatial feature is sufficient to produce that response, which facilitates the corresponding response on validly cued trials. However, this explanation fails to account for the finding that the Simon effect tended to disappear or reverse

(Proctor et al., 1992) or at least decrease (as compared to no-cue trials; Wühr, 2006) on invalidly cued trials. An alternative explanation is that preparation of a response activates the spatial code associated with the response, and the activation directs visual attention toward the location corresponding to the spatial code, facilitating encoding of stimuli on that location (Hasbroucq & Possamai, 1994; but see Proctor et al., 1992, and Verfaellie et al., 1988, which show that cuing stimulus location had no influence on the Simon effect). This seems to suggest that the phenomenon is akin to memory-driven attention capture (Downing, 2000) that has been discussed earlier. The explanation is consistent with the facilitation of the Simon effect on validly cued trials and the reduction on invalidly cued trials. It is also consistent with Wascher and Wolber's (2004) finding that response precuing increased the N2pc component of ERP, which is believed to reflect allocation of visual attention. Furthermore, an equally likely explanation of the phenomenon is that a response precue activates not only the spatial code but any LTM representations that are associated with the precued response. This would facilitate encoding of any stimuli associated with the response representation.

There have been few studies that investigated the role of response precuing in the Simon effect, so further explorations are necessary to provide better understanding of the phenomenon. In fact, some results are difficult to explain based on the current perspective. For instance, Buckolz et al. (1996) found no enhancement of the Simon effect when responses were precued by a letter ("L" or "R"). Also, Koch (2007) found the Simon effect to be reduced when participants could predict the response sequence in advance, which is in contrast to the effect of response precuing (but see Miles et al., 2010). Although more investigations are needed to examine the conditions under which the enhancement is obtained, the effect of response precuing still points to a close relationship between advance response preparation and stimulus processing.

Interference in Stimulus Encoding by Response Preparation

The emphasis on action in perception and cognition is not a new concept. For instance, Washburn (1916) proposed a motor theory to explain consciousness, and the motor theory of speech perception has been prominent for many years (Galantucci et al., 2006; Liberman & Mattingly, 1985). An even older action-oriented cognitive approach is that of ideomotor theory (e.g., James, 1890; see, Shin et al., 2010, for a review of contemporary versions), which states that imagining or thinking about sensory consequences of an action, or *action effect*, is sufficient to activate and prepare that action. Consistent with the theory, when certain effects always follow specific actions, presenting stimuli similar to the effects facilitates execution of the associated actions (see Hommel & Elsner, 2009, for a review). Also, it has been shown that the Simon effect can occur based on the compatibility between stimuli and action effects (Hommel, 1993; Yamaguchi & Proctor, 2009, 2011a). Because action effects are not present before responses are made, their influence can be attributed to anticipation of the action's consequences, consistent with ideomotor theory.

A contemporary version of the ideomotor theory is the *Theory of Event Coding* (TEC; Hommel, 2009; Hommel et al., 2001). According to TEC, any perceptual and action events are represented as event codes or event files, which consist of more elementary entities called feature codes that represent individual stimulus and response attributes (e.g., color, shape, location, etc.). When the actor perceives an event, all feature codes that comprise the perceptual event are activated and bound together to form an event file. Once this binding has occurred, the feature codes become unavailable to form other event codes. Consequently, perceiving or planning events that include these preoccupied features takes longer than usual because they have to be unbound to form another event file. That is, action planning and stimulus encoding must be

delayed. The idea of binding, originating from Treisman's (1988) feature integration theory,

enables TEC to predict the bidirectionality between perception and action, which is the major

advantage of the theory to account for findings that action preparation hampers, rather than

facilitates, encoding of compatible stimuli. This phenomenon is referred to as *blindness to*

compatibility (Müsseler & Hommel, 1997a) or compatibility blindness.

   In Müsseler and Hommel's (1997a) study, participants were presented an arrow stimulus

(S1) pointing to the left or right and made a sequence of two responses: simultaneous presses of

the left and right keys (R0), immediately followed by a press of the key spatially corresponding

to the arrow direction (R1). R0 triggered brief display of another arrow stimulus (S2), also

pointing to the left or right, which was responded to by a single press of the key corresponding to

the direction of S2 (R2) or verbally reporting the S2 direction at leisure after execution of R1. In

both cases, R2 was less accurate when R1 and S2 were spatially compatible than when they were

incompatible. This result was replicated when the words LEFT and RIGHT were used instead of

arrows for S1, to exclude S1-S2 similarity, and when S1 was incompatibly mapped to R1,

dissociating correspondence between S1 and S2 from that between R1 and S2. Also, Müsseler et

al. (2000) obtained similar results when S1 was omitted, requiring participants to press one key

on every two consecutive trials and then switch to the other. In subsequent studies, the

researchers also confirmed that compatibility blindness occurs when S2 requires detection

(presence/absence of S2) rather than classification (Müsseler & Hommel, 1997b), and that the

sensitivity measure (d') was lower for R1-compatible stimuli than for R1-incompatible stimuli

(Müsseler et al., 2001). Wühr and Müsseler (2001) found that compatibility blindness is not

bound to response execution; the effect was even larger when S2 was presented about 2000 ms

before R1 was executed than when it was presented at around the moment R1 was execution.

Thus, it is the preparation of a particular response that causes the blindness. In fact, the effect disappeared as soon as R1 was executed. These observations suggest that the compatibility blindness is not due to a refractory period associated with response execution. In consequence, the researchers concluded that preparation of R1 hampered, or blinded, S2 encoding when they were compatible.

However, some issues still remain in the studies of compatibility blindness. First et al. (2002) used the stop-signal paradigm (Logan & Cowan, 1984) and showed that the blindness occurred only on stop-signal trials, implying that active response inhibition may be involved. Also, some studies suggest that, without response preparation, processing of S1 still yields the compatibility blindness (e.g., Stevanovski et al., 2003). Hommel and Müsseler (2006) found that the blindness was modality specific (i.e., verbal vs. manual), whereas Kunde and Wühr (2003) found the opposite (see also Eder & Klauer, 2009). Moreover, Koch and Prinz (2002, 2005) used an experimental design that was similar to Müsseler and Hommel's task, but did not obtain the blindness effect. Instead, they found that R1 was faster when it was compatible with S2, a result not obtained in Müsseler and Hommel's (1997a) study. Thus, although several studies indicate that preparing a set of responses enhances processing of stimuli related to the responses (e.g., Bekkering & Neggers, 2002; Fagioli et al., 2007), there are unresolved issues concerning influences of preparing a particular response.

Action Field Theory

The three primers for the new framework presented here include (1) seemingly automatic processes are under control, or at least the influence, of one's intention, (2) new task-defined processes can be automatized without extensive training, and (3) attentional selection depends on prepared actions. Encoding of task-irrelevant stimulus features is determined at least in part by

the type of action required to perform the task. These results agree with the *selection-for-action view* (Allport, 1987; Humphreys & Riddoch, 2005), which states that processing of stimulus information is enhanced if it is relevant to a prepared action, whereas processing that is not related to the action is degraded. The Action Field Theory proposed here is consistent with the selection-for-action view, but it goes further by integrating this notion into the memory-based theory of cognitive control in which each task episode is stored as a separate instance in memory (Logan, 1988). The main purpose of the Action Field Theory is to formulate the roles of memory and action in automaticity of cognitive control.

The memory view of automaticity has been elaborated into a more general framework for modeling attention and memory phenomena (*Instance Theory of Attention and Memory*, or ITAM; Logan, 2002). As in the original theory, ITAM assumes instance retrieval as the basis of response selection. The retrieval process uses similarity-based matching between the current set of stimuli and the instances of past events. That is, encoded stimuli become efficient retrieval cues for instances stored in LTM to the degree that the stimuli are similar to the features recorded in the instances. An important extension of this instance-based response-selection mechanism in the Action Field Theory is the constraint imposed to the types of instances that can effectively be retrieved in a given context. First, it is assumed that the probability of instance retrieval depends on the pre-activation (or base activation rate) of the instance. That is, certain instances are activated prior to stimulus onset, and these instances can be retrieved whenever associated stimuli are encoded, which results in automatic response activation associated with those instances. On the other hand, other instances are deactivated at the time of stimulus onset, so they cannot be retrieved automatically when associated stimuli are encoded. To retrieve these instances, attention must be shifted to them, so that they can be retrieved intentionally. Thus, the

retrieval probability of deactivated instances is close to zero unless focus of attention is shifted to them. Hence, not all instances are equal in the Action Field Theory, because automatic retrieval is a function of the amount of pre-activation.

Furthermore, the pre-activation of instances is determined by response preparation. That is, response preparation enhances activation of response representations, and this activation spreads to associated instances according to the relatedness of these instances to the response representations. Consequently, stimuli become efficient retrieval cues and elicit automatic retrieval only if they are closely associated with prepared actions. In other words, automatic memory retrieval is determined by the relation between the instances and the action representations. In this manner, the Action Field Theory integrates the notion of action-based selection into the framework of instance-based models of attention and memory. To illustrate the present framework in more detail, the remaining sections discuss three principles of the Action Field Theory.

First Principle: Instance Representation

One of the core assumptions of the Action Field Theory is that response selection is performed by retrieving an instance in memory. Specific task-episodes are assumed to be stored as separate instances that record actions taken in a particular context. These actions are selected and implemented upon retrieval. Moreover, any contextual information present at the creation of an instance serves as a retrieval cue for that instance, so an S-R association is preserved in an instance. There is redundancy among instances that represent similar task episodes in which the same S-R association occurs, and the redundancy is important in the theory because it determines the probability of instance retrieval reflecting the strength of S-R association. In principle, therefore, the probability and speed of retrieving an instance increase with the number of similar

instances stored in the memory (Logan, 1988). The original instance theory distinguished response selection based on memory retrieval from that based on algorithms, but the theory left mechanisms underlying the algorithmic processes unspecified because there could be many different algorithms to perform the same task (Logan, 1989). In the present framework, however, algorithmic processes are also based on memory retrieval.

The difference between automatic and controlled processes is that the former can be achieved by a 'one-shot' memory retrieval, whereas the latter requires a series of memory retrievals. For instance, once automatized, addition can be performed when an equation triggers the answer from memory without intermediate steps (e.g., the stimulus "3 + 2" cues the instance "3 + 2 = 5"). Before being automatized, the same addition may require retrieval of an instance that links an operand to a physical action ("3" cues "raising three fingers") and another instance that links another operand to another physical action ("2" cues "raising two fingers"). Then, the actor would retrieve instances that represent digits in a sequence until all fingers have been assigned a digit, which constitutes counting the number of fingers. This is obviously not the only way to formulate the processes of performing addition, but the example illustrates the fact that memory retrieval is sufficient to perform algorithmic operations. Furthermore, more complex tasks would require a recurrent process of deliberately searching candidate instances in the memory storage and rejecting them until one is satisfied with the current solution. This process requires shifting the attentional focus across the memory pool (Cowan, 1995). A shift of the attentional focus also changes the background activation of instances in such a way that activation of instances that are associated with the current focus of attention increases. The activation gradually dissipates as attention shifts away. This may be illustrated by the finding that the response congruity effect can occasionally interact with task sequence without being

influenced by CTI, in such a way that the effect is larger when the task switches than when it repeats (e.g., Yamaguchi & Proctor, 2011a), suggesting that shift of the attentional focus still affects automatic processes that reside outside the attentional focus. Consequently, certain instances are retrieved more easily than others, depending on the relationship with the current attentional focus (Oberauer, 2002).

As discussed earlier, the current perspective is in contrast to the modal view of automaticity. The principle of instance representation is crucial in that it allows automatic processes to operate conditionally upon the task goal, and task-defined, temporary S-R associations to be implemented in an automatic fashion. Thus, the principle of instance representation gives a reasonable mechanism behind the interplay between automatic and controlled processes. At the same time, the current perspective is compatible with another prominent approach in cognitive psychology, the connectionist framework (e.g., Rumelhart et al., 1986). Connectionist models have been developed for Stroop interference (e.g., Cohen et al., 1990; Phaf et al., 1990) and for the Simon effect (Zorzi & Umiltà, 1995). A difference from our approach is that the connectionist models assume the strength of S-R associations to be the driving force of response activation, whereas the instance theory assumes the number of similar instances as the determinant of response activation, but this difference may be a minor detail. At a computational level, the instance approach and the connectionist framework likely mimic each other, unless further assumptions are made in particular task contexts to restrict predictions of specific model instances (e.g., Tagliabue et al., 2000), although the present approach arguably offers a more intuitive conceptualization of the interplay between automatic and controlled processes than the connectionist representation.

Second Principle: Compound-Cue Retrieval

Not all stimuli are encoded automatically. This is illustrated by the observation that a stimulus produces Stroop interference or the Simon effect only when the task necessitates processing of that stimulus, for example, by having a subliminal prime identical with the target stimulus (Eimer & Schlaghecken, 1998), by presenting extra stimuli that requires identifying a stimulus attribute uninformative of the correct response (O'Leary & Barber, 1993), or by pre-activating LTM directing visual attention to similar stimuli (Downing, 2000). In either case, task-irrelevant stimuli can get encoded, and, once encoded, they affect response selection. That is, all encoded stimuli act together in retrieving an associated instance and activates a corresponding response. This is the principle of compound-cue retrieval. The principle is a primary assumption in the memory view of automaticity (Logan, 1988) and is central in the explanation of the task-switching cost without involvement of central executive (Logan & Bundesen, 2003; Logan & Schneider, 2010; Schneider & Logan, 2005, 2009). Each stimulus present at the current context is potentially an effective cue to retrieve instances that contain the stimulus as a feature of the past task episodes. Instance retrieval becomes obligatory when the stimulus is encoded, but competition among activated instances allows only a limited number of instances (typically, a single instance) to actually be retrieved. The competitiveness of an instance for retrieval is a function of matching between the instance and each of the encoded stimuli, which determines the similarity between the instance and the current task context. Thus, the more similar the instance is to the current trial, the more likely and the more quickly it is retrieved (e.g., Yamaguchi & Proctor, 2009). The response associated with the instance is, then, selected and executed. Therefore, response selection is determined by the set of encoded stimuli that form a compound retrieval cue as a whole.

The compound-cue retrieval model of task switching is aligned well with connectionist

models (e.g., Cohen et al., 1990; Phaf et al., 1990; Zhang et al., 1999; Zorzi & Umiltà, 1995) that assume coactivation of a response code by multiple S-R associations. This assumption is consistent with the findings, for example, that the Simon effect occurs based on multiple feature dimensions (e.g., Lamberts et al., 1992; Lleras et al., 2004; Wühr et al., 2008). Yet, an alternative perspective has been proposed to explain the role of stimulus-response compatibility in Stroop interference (Virzi & Egeth, 1985; see also Palef, 1978), which is known as the *translational account* (also see Magen & Cohen, 2007). The translational account states that stimulus features are processed separately by modality-specific analyzers that operate in parallel. If stimuli and responses belong to the same modality, stimuli can directly activate the responses; if they belong to different modalities, however, the stimuli have to be translated into the response modality. Thus, from this perspective, stimulus-response compatibility means that stimuli and responses belong to the same modality (also see, Kornblum et al., 1990). When responses are compatible with task-irrelevant stimuli than task-relevant ones, Stroop interference occurs because the task-relevant stimuli have to be translated into the analyzer that processes the task-irrelevant stimuli, in which response competition occurs. However, the interference does not occur when responses are compatible with the task-relevant stimuli because there is no translation across analyzers and no competition between the task-relevant and -irrelevant stimuli. Although the translational account places an emphasis on the role of response in stimulus processing as in the Action Field Theory, a number of observations suggest difficulty of the translational approach.

The central tenet of the translational account is that response competition does not occur as long as stimuli are processed in different modules, and translation is necessary only if task-relevant stimuli are incompatible with responses. Thus, response competition should not occur when task-relevant stimuli are compatible with responses. As mentioned, however, studies have

found reversed Stroop interference from task-irrelevant locations when participants read spatial words or from word-meaning when participants pressed keys to word locations (e.g., Lu & Proctor, 2001; O'Leary & Barber, 1993), and it is a very common finding that the Simon effect emerges based on irrelevant word meaning when responses are keypresses (e.g., Proctor et al., 2009). A recent study also showed that the Simon effect can occur simultaneously based on multiple stimulus dimensions (e.g., numerosity and spatial location; Wühr et al., 2008), and there are cases where not only stimuli but also responses are multidimensional (e.g., Yamaguchi & Proctor, 2009, 2011a), for which it is difficult to talk about a single response modality. It is of course possible to assume that a response code consists of different elementary features that differ in modality (e.g., Hommel et al., 2001), and stimulus features activate the respective response features, but this implies that multiple stimulus features coactivate a response code as a whole. Therefore, although the translational account is an attractive concept in explaining the role of responses in Stroop interference, the notion does not seem to have an empirical or logical advantage over the compound-cue retrieval theory.

Third Principle: Action-Based Selection

The main thesis of the Action Field Theory is that preparation of a certain response set determines processing of task-irrelevant stimuli. It assumes that activation of response representations increases with response preparation and spreads to other instances that are associated with the prepared actions. This establishes an "Action Field" in the memory pool. The spreading activation facilitates processing of response-relevant stimulus information, and automatic processes arise from the Action Field. This is the principle of action-based selection. In addition to the evidence reviewed in the earlier sections, Valle-Inclán and Redondo (1998) also showed, using the LRP, that onset of a stimulus triggers activation of a spatially compatible

response only when participants are informed about the task-relevant S-R mapping before the stimulus onset but not when the mappings are informed after a stimulus has been presented. Thus, automatic response activation seems to require preparing a particular set of actions in response to pre-specified stimuli.

The Action Field Theory emphasizes selection across dimensions rather than individual features. This emphasis is in line with theories of visual attention (e.g., Müller & Krummenacher, 2006; Treisman, 1988) as well as with the fact that the role of stimulus-response compatibility in Stroop interference is at a *set level* rather than an *element level* (Kornblum et al. 1990). That is, the occurrence of Stroop interference depends on the prepared set of responses (e.g., saying the names of the colors red, green, and blue; Proctor, 1978) as opposed to an element of the set (e.g., saying "red"). This may be because performing a task requires increasing the readiness of all alternative responses rather than that of an individual response. This assumption seems consistent with the finding that the Simon effect is obtained based on features that discriminate alternative responses (Ansorge & Wühr, 2004), since the observation implies that it is the contrast between alternatives, rather than characteristics of an individual response, that give rise to the Simon effect. Likewise, Hommel (2010) proposed the *action-induced attention model*, which states that attention weights of perceptual dimensions are biased according to action-relevance of the dimensions. The present framework agrees with this proposal. Yet, there are also findings implying an element-level influence of action representation (e.g., Müsseler & Hommel, 1997a). Although empirical clarifications are yet to be established for these observations, as pointed out earlier, future investigations might prove that the distinction between set- and element-levels is indeed inconsequential.

Instead, the current framework can be compared to that of TEC, which also explains

action-based selection. A most unique assumption of the TEC framework is that of feature binding, according to which a task episode is constructed by binding a set of elementary feature representations, or feature codes (Hommel et al., 2001). The binding mechanism is not necessarily a new concept (e.g., Treisman, 1988), but its application to stimulus-response compatibility effects and related phenomena was a novel approach. In particular, the TEC account of compatibility blindness (i.e., the occupation hypothesis; Stoet & Hommel, 1999) is a unique idea that represents the strength of the TEC framework. At the same time, however, this prediction also raises some issues. The fundamental assumption underlying the TEC concept is sharing of feature codes by multiple event files. The theory can account for the Simon effect, for example, by assuming that stimulus and response representations share a feature code if they are compatible, so that activating the stimulus representation partially activates the response representation as well. Likewise, TEC accounts for compatibility blindness by assuming that a feature code that belongs to a stimulus becomes unavailable if the code has been integrated into another event file that represents planning of an action. A problem is that it is not clear as to which of these opposing effects will occur in a given condition (cf. Koch & Prinz, 2005 vs. Müsseler & Hommel, 1997a). However, this problem may not be fundamental if it is only a matter of gathering more data and evidence that allow discriminating conditions in which these opposing effects are obtained.

More problematic is a second issue, that two event files are not allowed to contain the same feature code at the same time. The unique predictions of TEC depend on this assumption. For example, the occupation hypothesis does not arise from the theory if more than one feature code can exist for a particular contextual feature and can be integrated separately into different event files. Also, coactivation of event files (i.e., the stimulus-response compatibility effect)

would not occur if multiple feature codes exist that represent the same feature. Thus, the assumption that a single feature code is shared by multiple event files is fundamental in TEC. Instances in the Action Field Theory are similar to event files, in that both assume a task episode that is a collection of features, but the Action Field Theory differs from TEC in that it does not assume a single representation for each feature. Thus, multiple task episodes can contain the same feature code at the same time. This assumption seems to be more consistent with studies that have examined transfer of incompatible S-R mappings to the Simon task (e.g., Proctor & Lu, 1999). In the experimental procedure, participants first perform an incompatible-mapping task for which they respond to stimulus locations by pressing spatially incompatible keys. Subsequently, participants transfer to the Simon task, for which the Simon effect is typically eliminated or reversed (e.g., Proctor & Lu, 1999). This transfer effect does not appear to replace the existing Simon effect. Instead, the effect gradually develops as the amount of the incompatible-mapping trials increases (Proctor et al., 2007; Proctor et al., 2009; see MacLeod & Dunbar, 1988, for similar results in a Stroop-like task). Thus, in the course of reversal, there must be a phase in which the preexisting S-R associations compete against newly acquired associations (see also, Tagliabue et al., 2000). Such results suggest that a feature code can exist in multiple event files at the same time, in contrast to the TEC assumption. The Action Field Theory states that task episodes are stored as separate instances, so it does not suffer from the same constraint as TEC. Hence, the findings in the transfer studies are consistent with the Action Field Theory. Although the Action Field Theory may be reformulated to incorporate the TEC-like feature binding without altering other components (see, e.g., Cowan, 1995; Oberauer, 2005), it does not appear to be an urgent issue at the current stage of theory development.

General Discussion

The present theoretical review focused on experimental paradigms in which selective attention across feature dimensions plays a central role in optimizing task performance. While performing the Stroop task, for example, efforts must be made to focus attention on the colors of words in order to satisfy requirements of naming the colors rather than reading the words. Although researchers have thought of this interference effect as arising from an overlearned tendency to read words, that apparently is not the case. Instead, the difficulty of focusing on the relevant stimulus dimension is due to the fact that the task involves an irrelevant dimension that is more compatible with the required response. In fact, the effect can be eliminated when responses are replaced with those that are more compatible with the relevant dimension, indicating that the effect depends on what responses are required and prepared to perform the task. Unfortunately, however, the once dominant accounts of stimulus-response compatibility (dual-route models) are not suggestive of the underlying mechanisms for this selection bias in that they merely reiterate the automatic-controlled distinction that was devised to describe Stroop interference but has been refuted by contemporary researchers. A problem of such a modal view is that no mechanism is specified, so the account does not provide useful implications about the nature of performance. Instead, an alternative perspective suggests that memory-based response selection is what leads to automaticity of performance. The theory also proposes that there is no qualitative difference between mechanisms that underlie automatic processes and those that underlie controlled processes. Evidence supporting this proposition is abundant in recent studies investigating cognitive control, such as dual-task and task-switching studies, as well as in the literature concerning sequential modulations of interference effects. These studies agree that cognitive control is achieved by automatic retrieval of task episodes from memory. Furthermore, it is argued here that the unitary view of memory and attention, which shares the assumption

with the instance theory regarding the basic mechanism of response selection, provides an important distinction between WM (focus of attention) and STM (activated LTM). This distinction explains how automatic processes are dependent on contextual and intentional factors that are incompatible with the traditional modal view of automaticity underlying the dual-route models of stimulus-response compatibility and the automaticity account of Stroop interference. The distinction is also critical in accounting for findings that dissociate between aspects of performance that reflect capacity limitation and aspects that do not (e.g., task-switching cost vs. response congruity effect, list-length effect vs. intrusion effect, etc.). Based on these conceptions, I synthesized the Action Field Theory. The main thesis of the theory is that activation of instances in memory depends on action preparation. Results of recent studies are supportive of the present thesis, showing enhancement of processing action-relevant feature dimensions.

Resolving the Paradox

The instance theory states that memory retrieval presumes stimulus encoding, and stimulus encoding registers cues that initiate memory retrieval. To control automatic processes, one could manipulate retrieval cues by changing (1) the current state, (2) the focus of attention, or (3) the goals (Logan, 1989). In the present framework, the current state is equivalent to activated LTM. The activation of LTM depends on what is necessary to perform the task; that is, the overall task goal and the immediate goals (sub-goals) that need to be attained to meet the overall goal (cf. Anderson & Lebiere, 1998). The focus of attention at any given moment is determined by shifting attention between these sub-goals. In most experiments (if not all), one of such sub-goals is to make a choice and report it by executing a specific action. Thus, a set of action representations is always active in the background, even if they are not at the immediate focus of attention. Stroop interference and the Simon effect are robust and difficult to eliminate

because action representations must always be activated in performing the tasks, and stimuli always contain action features. Several factors determine the likelihood of these features being encoded, such as the eccentricity or categorical similarity to the target stimuli (Kahneman & Chajczyk, 1983; Miles et al., 2009) and the nature of the task that these stimuli are required to process (O'Leary & Barber, 1993). Attention tends to be attracted toward these features because action representations are active, as the memory-driven attention capture suggests (Downing, 2000). Consequently, the response-overlapping stimuli are encoded and serve as retrieval cues for the action representations even if the stimuli are not appropriate in a given context. The influence of action-relevant features may be reduced by increasing attentional weights for other feature dimensions. However, it is less likely that the underlying processing will be entirely inhibited (Jacoby et al., 2003; Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1982) because that requires suppression of action representations and makes selection and execution of these actions very difficult. This explains why Stroop interference and the Simon effect are so robust and difficult to eliminate.

Further Extensions of the Framework

Although the present article is concerned only with the conceptual framework for selection across feature dimensions, formal models that encompass the principles of the theory are easily conceivable. For instance, Logan's (2002) ITAM provides a main quantitative framework for instance-based models that involve the principle of compound-cue retrieval as well as the principle of instance representation. The framework can be elaborated by incorporating the principle of action-based selection as a bias-determining factor in a systematic fashion. Logan's (1996) CODE Theory of Visual Attention (CTVA) assumes that stimuli are stochastically distributed across space as partially overlapping representations, and the observer

perceives the stimuli by setting a threshold at an arbitrary value. Physically distinct stimuli are perceived as a single object when their representations overlap at the threshold, but they appear to be separate objects when their representations do not overlap. CTVA potentially provides mechanics that are useful to quantitatively define regions of activated LTM. Alternatively, Yamaguchi and Proctor (2012) developed the *multidimensional vector* (MDV) *model*, a mathematical modeling framework for choice-reaction performance, that assumes a multidimensional psychological space as the basis of response selection. MDV proposes that the subjective utility (or discriminability) of stimuli is determined by a joint product of stimulus and response attributes, and this is one way to instantiate the principle of action-based selection in a systematic manner. Also, MDV assumes multidimensional representation of stimuli and responses that are compatible with the principles of compound-cue retrieval and instance representation, considering the psychological space as the Action Field. Therefore, the present approach appears promising in providing a conceptual framework for future developments of rigorous quantitative models of choice performance. A challenge of the framework is that it is concerned only with tasks that are as simple as choice reactions. The emphasis of simple tasks is certainly valid, given that they are primary vehicles in the studies of cognitive processes and mechanisms. It is possible that control of actions in more complex tasks may involve something more than memory retrieval, but it is equally possible that performance in complex tasks can be conceived of a series of simple routines that operate based on memory retrieval. For example, the hierarchical theory of skilled performance (Logan & Crump, 2011; Logan, 2018) mostly rely on memory retrieval. Thus, performance of complex tasks may be accounted for by an extension of the Action Field Theory. If so, the principles discussed in the present article should still hold in complex task settings as well. This possibility should be subjected to future scrutiny.

Concluding Remarks

The distinction between controlled and automatic processes has been popular in many fields of cognitive psychology. It has provided a convenient, and powerful, language to explain a range of psychological phenomena. However, characteristics that are attached to these processes are often violated, and there are theories of automaticity that do not characterize these processes in terms of operational criteria (e.g., Logan, 1988). As introduced in the present review, recent studies provided evidence that automatic processes are not independent of the actor's intention. At the same time, it has been shown that intentional processes involve characteristics that are usually attached to automatic processes. Whereas many psychological theories assume independent contributions of automatic and controlled processes, there are few theories that describe how the automatic and intentional processes interplay. The Action Field Theory is one such theory highlighting the fact that automatic processes operate in accordance with the actor's intention to implement certain actions. This is achieved by putting the preparatory state at the beginning of psychological processes (Hommel, 2000b; Logan, 1978). Thus, rather than assuming the physical stimuli as the starting point of the psychological processes, the present perspective emphasizes that the actor's internal state is the appropriate stating point of the cognitive chain (Prinz, 1997; Thurstone, 1927; Tolman, 1949). That is, automatic selection of stimulus features depends on how people are prepared to act on the environment.

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