

# Understanding Central Processes: The Case against Simple Stimulus-Response Associations and for Complex Task Representation

Eliot Hazeltine<sup>\*,1</sup> and Eric H. Schumacher<sup>§,1</sup>

<sup>\*</sup>Department of Psychological and Brain Sciences, The University of Iowa, Iowa City, IA, USA

<sup>§</sup>School of Psychology, Georgia Institute of Technology, Atlanta, GA, USA

<sup>1</sup>Corresponding authors: E-mail: eliot-hazeltine@uiowa.edu; eschu@gatech.edu

## Contents

1. Introduction	196
1.1 Response Selection	196
1.2 Investigating Central Processes	197
1.3 Two Limitations of the Simple S-R Association View	200
2. Task Switching	201
3. Hick—Hyman Law	204
4. Stimulus-Response Compatibility	205
5. Congruency	207
5.1 Within-Task Congruency	207
5.2 Between-Task Congruency	209
6. Dual-Task Performance	211
6.1 Single-Channel Models	212
6.2 Crosstalk	215
7. Task Configuration	216
7.1 Cross-Trial Control	217
7.2 Partial Task Precuing	219
8. Learning and Practice	220
8.1 Nonhuman Animal Learning	220
8.2 Human Learning and Practice	222
9. Memory	225
9.1 Priming	225
9.2 Explicit Memory	226
10. Summary of the Behavioral Phenomena	226
11. Task Set Representation in the Human Brain	228
11.1 Prefrontal Cortex	228
11.2 Characterizing Control-Related Neural Activity	230

12. General Comments	231
Acknowledgments	233
References	234

## Abstract

The act of choosing an action based on stimulus information and a set of arbitrary rules is termed response selection. It embodies the core of voluntary behavior and plays a critical role in most experimental tasks, yet the processes supporting it are poorly understood. Often, response selection is assumed to arise through the activation of stimulus-response (S-R) associations that bridge perceptual and motor processes. As others have pointed out before us, this conceptualization does little to account for many findings relating to choice response tasks. In the present chapter, we describe data from eight areas of research that bear on theories of response selection: task switching, the Hick—Hyman law, S-R compatibility, congruency effects, dual-task performance, task configuration, learning, and memory. We then turn to neuroimaging and neurophysiological data and examine what they indicate about how stimulus information can be flexibly mapped to motor output. Across these diverse domains, the shortcomings of the simple S-R association view consistently cohere around two related properties: First, conceptual aspects of the task trump physical properties of the stimulus and responses with regard to determining the varying demands on central processes. Second, task representations are highly structured, such that some actions are more closely related than others, and these relationships affect performance. We conclude by delineating alternative theoretical frameworks that might better capture the nature of the central processes supporting response selection.



---

## 1. INTRODUCTION

A hallmark of human behavior is flexibility. Humans can be given a novel set of instructions and perform them accurately without feedback or external reward. To do this, we must adaptively configure cognitive processes to match our goal states with the current task demands (Allport, Styles, & Hsieh, 1994; Duncan & Owen, 2000; Monsell & Driver, 2000; Norman & Shallice, 1986; Rogers & Monsell, 1995; Schneider & Shiffrin, 1977). These demands can entail a tremendous range of stimuli and responses, and the mappings between stimuli and responses can be arbitrary and dynamic. Yet, how we are able to make any voluntary response to any consciously perceived stimulus remains mysterious.

### 1.1 Response Selection

This operation of producing a response to a stimulus according to the current task goals is termed response selection. It is central to most voluntary

behaviors and plays a critical role in most experimental tasks, but its contribution to measures of behavior is often neglected. Here we review several key findings relating to response selection and describe what they indicate about underlying cognitive processes.

Central processes like response selection are difficult to study in part because they must be distinguished from the peripheral processes that are related to stimulus identification or the specification of motor parameters. Most experimental manipulations involve changes in the stimuli or the responses and therefore likely impact peripheral processes, so it can be difficult to isolate effects on central selection processes. For example, using left and right arrows instead of colors to indicate left and right button presses may shorten the central processes that translate the stimulus to the response, but the change in stimuli will also affect perceptual processes that identify the stimuli. Because it may take more or less time to identify the direction of the arrow stimulus than to identify the color, it is difficult to attribute changes in performance to central or peripheral processes. The problem can work the other way as well: effects on central processes can also contaminate measures of peripheral processes. For example, as we argue below, learning-related improvements in performance assumed to reflect more efficient motor processing are in fact better characterized as altered response selection processes (e.g., [Hazeltine, 2002](#)). It is also unclear in some cases whether the origin of modulations in the sensitivity to stimulus information is perceptual or post-perceptual (e.g., [McCann & Johnston, 1992](#)).

A shared theme of both of the authors' collaborative and independent work is the examination of these central processes that allow individuals to take stimulus information and produce an appropriate response with minimal practice. Here, we review some findings that relate to the processes that support flexible, goal-based behavior. Our review is not exhaustive. We focus on findings that emphasize the complex nature of response selection processes along with related work from our own laboratories. Given the scope of the topic, we acknowledge that our coverage is skewed and incomplete, but our intention is to identify commonalities across a range of domains that motivate our investigations.

## 1.2 Investigating Central Processes

A popular approach to isolating central processes is to hold the stimuli and responses constant and manipulate the mappings between them (e.g., [Duncan, 1977b](#); [Fitts & Seeger, 1953](#); [Hazeltine, 2005](#); [Hommel, 1993](#); [Huestegge & Koch, 2010](#); [Kornblum, Hasbroucq, & Osman, 1990](#);

McCann & Johnston, 1992; Schumacher & D'Esposito, 2002; Simon & Rudell, 1967; Stoffels, 1996). For example, a condition in which a left arrow stimulus is mapped to a left response and right arrow stimulus is mapped to a right response can be compared to a condition in which the left arrow is mapped to the right response and the right arrow is mapped to the left response. Because the stimuli and responses are the same in both conditions, differences in response time (RT) when the mappings are changed can be attributed to central response selection processes.

A starting point for theoretical accounts of response selection is a concept borrowed from the behaviorist literature, the stimulus-response (S-R) association, which presumably bridges the perceptual and motor systems, allowing us to interact with our environments in a purposeful way. S-R associations can be instantiated in a variety of ways: they can take the form of links in a connectionist model between nodes representing stimuli and nodes representing responses (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Verguts & Notebaert, 2008) or they can take form of productions in a production system (e.g., Anderson, 1982; Anderson et al., 2004; Meyer & Kieras, 1997a,b; Salvucci & Taatgen, 2010). However, a common feature is that the presence of a particular stimulus activates a response in a feedforward fashion. That is, perceptual systems identify the stimulus, which in turn leads to the activation of the appropriate motor codes (e.g., Lien & Proctor, 2002; McCann & Johnston, 1992; Miller, 1988; Pashler, 1984).

The activation of an S-R association presumably allows stimulus information to initiate the planning and production of motor movements, but there is enduring controversy about whether, and to what extent, the relevant processes (e.g., stimulus perception, response selection, and motor preparation) work in a serial or parallel fashion. Early theories suggested that they were organized as a series of serial stages (e.g., Sternberg, 1969), so that perceptual processes completely analyzed a stimulus before central selection processes began to map the stimulus to the response and so forth. Other theories proposed that processes worked in a much more parallel fashion—with stimulus information continuously informing response processes about the probability of a likely stimulus (e.g., Miller, 1988; Usher & McClelland, 2001).

In the present paper, we embrace the latter approach and further argue that S-R associations do not provide much explanatory power for understanding many critical aspects of goal-based behavior. Specifically, we assert that accounts based on S-R associations essentially elide the complex

operations that support response selection, opting instead to propose a set of stages (serial or parallel) that specify a sequence of representations that can be used to drive goal-based behavior. They do not address the coding of higher-level aspects of the tasks incorporating relationships between sets of stimuli and sets of responses—that is, they operate only on the “atomic” level of individual stimuli and individual responses. This atomic conceptualization is insufficient to explain the findings we review below.

Part of our motivation for explicating these shortcomings comes from challenges to the assumption that stimulus and response processing are distinct (e.g., Gallese, Fadiga, Fogassi, & Rizzolatti, 2002; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Mechsner, Kerzel, Knoblich, & Prinz, 2001; Müsseler & Hommel, 1997; Prinz, 1990). There are multiple alternative frameworks rejecting this claim but a common thread is that the perceptual and motor processes are intimately related and temporally overlapping (e.g., Cisek & Kalaska, 2005, 2010; Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Eriksen & Schultz, 1979; Gaskell & Marslen-Wilson, 2002; McClelland, 1979; Spivey, Dale, Knoblich, & Grosjean, 2010). Therefore, instead of assuming that the flow of information is primarily unidirectional, moving from representations of stimuli to representations of responses, these accounts emphasize the bidirectional flow of information so that motor states influence perception (e.g., Klatzky, Pellegrino, McCloskey, & Doherty, 1989; Müsseler & Hommel, 1997; Proffitt, 2006).

If it is accepted that stimulus and response processing are not distinct stages of processing, then the notion of an S-R association becomes less obviously useful. That is, without the idea of distinct, serial processing stages, the need for links between a completed representation of the stimulus and a representation of the responses diminishes. Expanding the concept of the S-R association to allow for multiple, bidirectional links between individual stimulus features and responses (or components of the response) becomes tantamount to acknowledging that perceptual information is eventually transformed into motor codes—a claim that is obviously true and provides little constraint on theory—unless the links are precisely specified. In short, the use of S-R associations is often used as shorthand for central processes, much as homuncular control systems serve as placeholders in theories of executive control. However, the conceptualization of response selection as the activation of an S-R association may be more damaging; appealing to a homunculus at least implicitly acknowledges that serious theoretical questions remain, whereas the notion

of an S-R association can imply that the translation process is understood, straightforward, and uninteresting.

### 1.3 Two Limitations of the Simple S-R Association View

In our review of the evidence against the usefulness of S-R associations for explaining voluntary behavior, we identify two primary shortcomings that may serve as categories to link findings across a range of procedures and phenomena. First, classically defined S-R associations are not rich enough to account for the patterns of transfer and flexibility of behavior reported in the literature. That is, compatibility and practice effects indicate that the encoded representations include more than just the integrated physical properties of the stimuli and responses and the mapping between them; rather, they incorporate conceptual and intentional properties of the stimuli and responses that are contingent on contextual factors. This widely recognized aspect of behavior indicates that the notion of an S-R association is too simplistic to account for the central processes that guide and select goal-based actions. We term this shortcoming the *conceptual problem*.

Second, the appropriate response to a stimulus varies according to the task and context, and the rules relating which responses are signaled by which stimuli are structured so that some rules are more closely related to others and some directly conflict. Most theorization about this aspect of behavior is based on the notion of a *task set*. Task sets are the mental representations that allow us to transform the welter of sensory information into meaningful goal-based behavior. They are often thought of as collections of individual S-R associations (e.g., [Lien, Ruthruff, Remington, & Johnston, 2005](#); [Logan, 1990](#); [Schneider & Anderson, 2011](#)). However, as we will argue, they include much more information that defines the boundaries of a task and facilitates learning and selection (cf., [Dreisbach, Goschke, & Haider, 2007](#); [Henson, Eckstein, Waszak, Frings, & Horner, 2014](#)). We propose that widely studied behavioral phenomena thought to reflect changes in stimulus processing or individual S-R associations are better characterized as reflecting changes in the representation of the task and argue the current understanding for how tasks are represented and how these representations guide the motor system is lacking. This gap must be addressed if we are to develop rigorous accounts of goal-based behavior that can span the complex task demands confronting humans in real world situations. We term this shortcoming the *structural problem*.

By showing the shortcomings of theoretical accounts that rely on simple S-R associations, we hope to specify what behavioral phenomena need to be

explained and to provide some initial steps based on behavioral and neural data as to how these can be addressed. We focus on eight core domains relating to the performance of choice reaction time tasks: task switching, the Hick–Hyman law, S–R compatibility, congruency effects, dual-task performance, task configuration, learning, and memory. We then examine what neuroimaging and neurophysiological studies indicate about central processes and task-set representation. We are not the first to describe these intriguingly complex aspects of response selection. Indeed, we review a broad range of work that has already established the general shortcomings of accounts relying solely on S–R associations. Our goal is to demonstrate commonalities in the findings across a range of experimental procedures and use these commonalities to delineate an approach for abandoning the reliance on the S–R association and developing an alternative theoretical framework.



---

## 2. TASK SWITCHING

Perhaps the most popular way to study how central processes are configured is with task-switching procedures. In typical task-switching studies, participants are given at least two sets of rules for how to respond to stimuli and switch between them on some successive trials. There is a considerable body of research examining the processes that underlie the activation of a task set so that a particular set of rules, which may conflict with other possible rules, determine how the participant responds to stimuli. The typical finding, especially when both tasks involve overlapping sets of stimuli, is that performance is slower on trials in which the task is switched from the previous trial compared to trials in which the task repeats (e.g., [Allport et al., 1994](#); [Jersild, 1927](#); [Rogers & Monsell, 1995](#)).

There are several findings in the task-switching literature that indicate that switch costs involve something other than just the activation of sets of S–R associations. For example, [Logan and Bundesen \(2003\)](#) argued that there is no switching of task rules in a cued task-switching procedure (but see, [Brass & Cramon, 2004](#); [Mayr & Kliegl, 2003](#)). Instead, participants solve the task in associative manner using the cue–stimulus conjunction as a cue. Alternatively, [Kleinsorge and Heuer \(1999\)](#) showed that the relationship between the tasks affects the magnitude of the costs and suggested that this phenomenon reflected the hierarchical organization of the rules. They proposed that the operations involved in the switch depend on the conceptual relationships among the tasks. They concluded that the task set

was best conceptualized as a multidimensional task-space as opposed to being composed of S-R associations, and switching involved selecting the appropriate control structure within this hierarchically organized space. These effects point to both conceptual (*viz.*, the multidimensional nature of task rules) and structural (*viz.*, the conditions under which switch costs occur) properties in task sets that are not captured by accounts based on S-R associations.

With regard to the conceptual nature of the task rules, [Mayr and Bryck \(2005\)](#) showed that response repetition costs can be observed even when both the stimuli are repeated but the rule used to determine which response is indicated by the stimulus is changed. That is, even on trials in which both the stimulus and the appropriate response are repeated, switch costs were observed when the underlying rule changed. Thus, the representations used by response selection processes include more than links between specific stimuli and specific responses; they appear to incorporate the underlying abstract rule linking the two together. This point was further demonstrated by the fact that the simpler horizontal switch and vertical switch rules were performed faster than the more complex clockwise and counterclockwise rules, indicating that a transformation was being applied to the stimulus to compute the appropriate response.

There is also evidence that rules, rather than simply S-R associations, can be hierarchically organized, which speaks to the richness of task-set representations. [Lien and Ruthruff \(2004\)](#) showed that factors that affect task-relatedness such as the timing and spatial layout of the stimuli can override task-switch costs. That is, when temporal and spatial factors encourage participants to conceptualize the sequence of responses as belonging to pairs, performing Task A followed by Task B (A-B) and then A-B again leads to more efficient performance than performing A-B then Task B followed by Task A (B-A). Thus, performing the same ensemble A-B consecutively is easier than switching the ensemble, even though AB-BA allows for the repetition of task B on the third trial. This finding suggests that it is not the loading of S-R mappings that produces the switch costs, given that the costs can be eliminated even when the new mappings must be loaded as the two element tasks are performed in rapid succession (see also, [Schneider & Logan, 2007](#)).

If abstract rules rather than S-R associations mediate response selection, then the same sets of S-R mappings might be encoded in multiple ways and indeed there is evidence to suggest this is the case. [Dreisbach, Goschke, and Haider \(2006, 2007\)](#) had participants learn to map eight stimuli to two

response buttons. The rule-based group of participants learned the mappings based on rules involving the color of the stimulus and a judgment. The S-R group simply learned that particular stimuli required particular responses without rules. The S-R group performed faster than the rule-based group. Moreover, the rule-based group showed switch costs, whereas the S-R group did not. Thus, there is evidence that response selection can involve distinct sets of central processes with different properties. [Dreisbach and Haider \(2008, 2009\)](#) provided further evidence that the task representation alters central processes by showing that rules can shield response selection from irrelevant stimulus information: when the task was encoded in terms of rules, performance was less susceptible to response conflict than when the task was encoded in terms of individual correspondences.

Further evidence from task-switching experiments for the idea that responses are selected via the implementation of conceptual rules rather than fixed S-R associations comes from [Schneider \(2014\)](#). He had participants switch between two tasks that could both be performed on visually presented noun words (small-large and living-nonliving) that were mapped to the same pair of response keys. Critically, words were never repeated, so there was no opportunity for associations between particular words and responses to be learned (see, [Waszak, Hommel, & Allport, 2003](#)). Nonetheless, there was a robust congruency effect, as words that indicated the same response for both tasks were performed more quickly than words that indicated different responses (see also, [Kiesel, Wendt, & Peters, 2007](#); [Koch & Allport, 2006](#); [Liefoghe, Wenke, & De Houwer, 2012](#); [Wenke, Gaschler, & Nattkemper, 2007](#)). Thus, this form of between-task congruency (see below) observed in task switching appears to be based on conflicting rules being applied to stimuli.

In sum, task switching costs likely derive from a range of factors, including the decoding of task cues, suppressing inappropriate mappings and reconfiguring selection processes (see, [Kiesel et al., 2010](#)). However, it is clear that the costs stem from more than simply loading sets of S-R associations in and out of working memory. Instead, switching sets appears to involve changing hierarchically organized task parameters, at least for certain types of tasks for which rules can be applied to capture relationships among multiple stimuli and responses. In such cases, the difficulty and stability of the switch depends on the relationship between tasks, and this is not easily explained when the tasks are reduced to sets of S-R associations.

Nevertheless, despite the prominence of this procedure in the study of task sets, there are other clues about the representation of task sets in domains

not captured by task switching. By its nature, task switching emphasizes processes involved in inhibiting one task set and activating another, but there are revealing effects regarding the nature of central processes even when the same task set is maintained across trials. We now turn to these other behavioral phenomena and examine how S-R associations fare in these domains.



### 3. HICK—HYMAN LAW

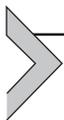
The Hick—Hyman law (HHL, [Hick, 1952](#); [Hyman, 1953](#)) is foundational to the information processing approach to cognitive psychology and describes the linear relationship between RT and the  $\log_2$  of the number of S-R alternatives, provided they are all equally likely. Note that the existence of this effect alone implies that structure of task sets are important, given that adding new S-R alternatives to all of the already learned S-R alternatives would have little effect on RT. It is adding new alternatives to the limited number within the task-set that produces the lawful increases. In short, if there were no task boundaries, then the addition of any new S-R alternatives would have the same negligible effect on RT for any tasks when added to the vast array of existing S-R rules.

This aspect of the HHL is seldom emphasized but has been addressed by [Schneider and Anderson \(2011\)](#). According to these researchers, the HHL results from the dilution of activation of S-R alternatives as the activation is spread across more S-R alternatives. Again, as with all accounts of the HHL, the notion of boundaries between task sets is essential; some S-R alternatives belong to the current task set and receive activation and others do not, instantiating a form of task structure. [Schneider and Anderson \(2011\)](#) assume that the HHL derives from the memory retrieval processes and the fan effect ([Anderson, 1976](#); [Watkins & Watkins, 1975](#)) as the task set becomes associated with more possible stimuli.

However, while the [Schneider and Anderson \(2011\)](#) account explains the set-specific nature of the HHL, there are other aspects of the phenomenon that are less easily accommodated by the model. [Wifall, Hazeltine, and Mordkoff \(2015\)](#) and others indicate that the number of responses is at least as important as the number of stimuli in determining the magnitude of the RT increase (see also, [Keele, 1970](#); [Laberge, Legrand, & Hobbie, 1969](#); [Laberge & Tweedy, 1964](#); [Pollack, 1959](#); [Rabbitt, 1959](#)). That is, adding four stimuli that are mapped to four different responses will lead to larger RT increases than adding four stimuli that are mapped to just two responses.

This finding is difficult to account for with models that assume that response selection occurs by allowing stimulus information to activate individual S-R associations in a feedforward way. Rather, it suggests that a set of response options are set up and compete for activation based on input (e.g., [Usher & McClelland, 2001](#)). It may be consistent with Duncan's *spatial transformation model* of the HHL (e.g., [Duncan, 1977a,b, 1978](#)). In this account, a set of operations are applied to the stimulus to compute the appropriate response and RTs increase with the complexity of the transformation (see also, [Mayr & Bryck, 2005](#)). If the duration of the transformation process depends on the number of responses given an arbitrary set of mappings, then this account may be able to account for why the number of responses also affects RT. However, other models of HHL include mechanisms analogous to a lookup table in which working memory is searched for the S-R association containing the observed stimulus (e.g., [Hawkins, MacKay, Holley, Friedin, & Cohen, 1973](#); [Theios, 1975](#)). Such an approach is not sufficient to explain the role that the number of responses plays in RT. Instead, the relative importance of the number of possible responses compared to the number of possible stimuli suggests that the instantiation of a task involves the establishment of a set of response options, which compete for activation given the available stimulus information.

In sum, even the HHL, which simply relates RT to the number of S-R alternatives, suggests that response selection processes engage representations that are both structured and conceptual. They appear structured because the law relates only to S-R alternatives within the current task, not all known alternatives. The representations appear conceptual because alternatives that share a response increase RT less than alternatives involving distinct responses, consistent with abstract codes that incorporate both stimulus and response properties.



#### 4. STIMULUS-RESPONSE COMPATIBILITY

Interactions between stimulus and response properties are perhaps most powerfully demonstrated by S-R compatibility effects, in which some pairings of stimuli with responses lead to better performance than other pairings. Like the HHL, S-R compatibility effects are some of the earliest described in the information processing tradition of cognitive psychology. [Fitts and Seeger \(1953\)](#) showed that RTs depended on an interaction between the stimulus set and response set, in effect demonstrating

what has since become *set-level* compatibility (see, Kornblum et al., 1990). In their first experiment, three stimulus sets (viz., an array of lights in a circle, a square, or a vertical and horizontal row) were factorially crossed with three response sets (organized in a circle, a square, or a horizontal and vertical row). The two factors interacted such that the optimal response set for one stimulus was different from the optimal response set for another stimulus set (e.g., circle response organization was optimal with the circular array of lights, the square responses with the square array and the row responses with the row stimulus array). This finding was interpreted as reflecting the number of recoding steps required to translate the stimulus to a response. In their second experiment, it was demonstrated that these differences persisted across 32 sessions of practice; a finding that is difficult to account for if one assumes that direct links are formed between stimuli and responses after practice. The critical contribution here for our purposes is that the relative ease with which an S-R pair is performed depends on the relationship between the stimulus set and the response set.

A second key finding relating to S-R compatibility was reported by Fitts and Deininger (1954) the following year. They used the four different stimulus displays and eight joystick responses from Fitts and Seeger (1953) and manipulated the mapping between the stimuli and responses. Crossing the three stimulus sets with the three mappings revealed a significant interaction between the two factors, indicating that the effect of mapping was much greater for one set of stimuli than for the other sets, consistent with what is now termed *element-level* compatibility (again, see, Kornblum et al., 1990).

Accounts that rely on S-R associations do not readily provide an explanation for these forms of compatibility. The usual approach to accommodating such findings is to assume that there are additional S-R associations, established outside the experiment, that co-activate the compatible response, thereby facilitating performance when the correct response is compatible and slowing performance when it is incompatible (see, Kornblum & Lee, 1995; Lien & Proctor, 2002). However, this framework poses at least as many questions as it aims to answer. For example, why are these latent, compatible S-R associations activated only when certain combinations of stimuli and responses present in the task set? That is, the compatible association between the leftmost stimulus and leftmost response is only activated when the other possible stimuli make that stimulus the leftmost and the other possible responses make the corresponding response the leftmost. This highlights both the conceptual and structural limitation identified above. If S-R associations are invoked to explain S-R compatibility,

then they must be defined conceptually and in relation to the other S-R associations within the task set but not those outside it. The same individual S-R association may be compatible or incompatible depending on the mappings of other stimuli in the task set (e.g., [Duncan, 1977b, 1978](#)).

Brain activation studies of S-R compatibility are also consistent with the idea that response selection involves more than simple S-R associations. Different regions within the prefrontal cortex have been shown to be sensitive to response selection difficulty effects like S-R compatibility depending on the stimuli (e.g., spatial or nonspatial) and responses (manual or vocal) ([Nagel, Schumacher, Goebel, & D'Esposito, 2008](#); [Schumacher, Elston, & D'Esposito, 2003](#)). If response selection simply activated an abstract representation of a response based on an abstract representation of a stimulus, then it's not obvious why different brain regions would be involved depending on stimulus and response modality. However, if response selection involves processing more complex information, then it makes sense that different brain regions might be involved depending on the modalities of the stimuli and responses and how they are paired.



---

## 5. CONGRUENCY

The results from the studies of S-R compatibility demonstrate that the relationship between the relevant features of the stimuli and the differentiating features of the responses affects response selection, but stimulus information that is not part of the S-R mapping can also impact performance. This information can simply be irrelevant, as in studies of within-task congruency, or it can be relevant for the selection of a separate response, as in studies of between-task congruency. While this difference may seem subtle, the two literatures are largely distinct, so we will discuss each of them in turn.

### 5.1 Within-Task Congruency

Congruency effects are most frequently studied under conditions in which participants perform a single task and must ignore some irrelevant stimulus feature that unpredictably indicates the correct or incorrect response. There are three widely used tasks for examining within-task congruency: the Stroop task ([Stroop, 1935](#)), the Simon task ([Simon, 1969](#); [Simon & Rudell, 1967](#)), and the flanker task ([Eriksen & Eriksen, 1974](#)). Here, we focus on the Simon task, in which participants are presented with a stimulus whose

irrelevant location corresponds or does not correspond with the location of the correct response. A behavioral advantage is typically observed when the locations of the stimulus and the response correspond (i.e., a congruent trial) compared to when they do not (i.e., an incongruent trial), but several aspects of the Simon Effect indicate that it does not simply result from S-R associations between the side of the stimulus and the side of the response.

First, [Wallace \(1971\)](#) demonstrated that the congruency advantage depended on the location of the keys, not the anatomical effectors. Thus, when participants crossed their hands, so that the left hand was placed on the right key and the right hand was placed on the left key, responses were faster when the location of the stimulus matched the location of the key rather than the side of the effector. This finding indicates the correspondence effect does not involve motor programs but instead relates to abstract codes (see also, [Hammond & Barber, 1978](#); [Hommel, 1993](#)). Furthermore, [Guiard \(1983\)](#) showed that the same physical movement (rotating a wheel) produced in response to the same stimulus could be congruent or incongruent depending on how that movement was conceptualized (e.g., as a wheel rotation vs as a hand movement).

Perhaps the most dramatic demonstration of the abstract nature of the Simon effect comes from [Hedge and Marsh \(1975\)](#), who showed that when S-R translation involves the reversal of relevant stimulus information, the Simon effect reverses. In their study, participants were instructed to press a red button when they saw a green stimulus and a green button when they saw a red stimulus. The buttons were in a horizontal row and the stimuli appeared to the left and right of the screen. Under these conditions, participants were faster when the stimulus occurred on the opposite side of the response. That is, reversing one relationship of the task (between the relevant stimulus color to response key color) caused the correspondence effect between another relationship of the task (between the irrelevant stimulus location and the response key location) to also reverse. This is another example of the conceptual limitation of traditional S-R association accounts. Why should reversing the S-R associations between the stimulus colors and the key colors affect the S-R associations between the stimulus locations and key locations?

These findings indicate that stimulus and response processing are intimately linked and difficult to explain with theories of central processes that assume that stimulus classification and response selection occur in discrete stages (see, [Hazeltine, Akçay, & Mordkoff, 2011](#); [Hommel, 2011](#); [Mordkoff & Hazeltine, 2011](#)), leading some to propose alternative models

that integrate perceptual and motor processing. For example, the event coding account (Hommel et al., 2001) holds that stimulus and response information are integrated into event files, which support the production of goal-based actions (see also, Hommel, 2004). When a left stimulus must be bound into an event file with a right response, there may be conflict as the left feature of the stimulus may be incorrectly bound to the response. This approach does not provide a straightforward account of all aspects of the Simon Effect (e.g., De Jong, Liang, & Lauber, 1994; Hazeltine, Akçay, et al., 2011; Hedge & Marsh, 1975), but it does offer a foothold on how stimulus and response features appear to directly interact. Conceptual information could be integrated into event files, although there is little consideration of structure and how boundaries are instantiated between sets of S-R associations. In other words, the theory readily addresses the conceptual problem (because contextual information may also be included in the event files) but not the structural problem (because it does not explain under what situations Simon Effects should be enhanced or attenuated). Also, the mechanism as described is purely associative, linking particular features of the stimuli and responses, making it ill-suited to accommodate findings that suggest tasks are encoded as rules and can be hierarchically organized (e.g., Dreisbach et al., 2007; Hazeltine, 2005; Kleinsorge & Heuer, 1999; Mayr & Bryck, 2005). However, one might modify the account and propose something akin to “task files” that include collections of mappings so that some S-R associations are more closely related than others.

## 5.2 Between-Task Congruency

In addition to congruency effects between irrelevant stimulus information and the appropriate response, there can be congruency effects between ongoing operations for distinct, concurrent S-R translations, such as when we respond to one stimulus with one hand and another stimulus with the other hand. Congruency effects between concurrently performed tasks are often large compared to those associated with more traditional within-task congruency effects that rely on irrelevant information, presumably because task-relevant information activates representations more strongly than to-be-ignored stimulus features. An advantage to studying central processes by manipulating between-task congruency beyond the large magnitude of the effect is that arbitrary mappings can be used. Thus, in contrast to typical within-task congruency manipulations, researchers do not have to rely on pre-existing correspondences between stimulus features or between stimulus features and responses. The principal finding is that when people make two

manual responses in close temporal proximity, the ease of responding depends on the similarity between the two movements (e.g., Kelso, Southard, & Goodman, 1979) and features of the appropriate movement for one hand can be observed in the movement of the other hand (e.g., Franz, Eliassen, Ivry, & Gazzaniga, 1996). This bimanual crosstalk phenomenon has been taken as evidence that motor codes are transmitted to the wrong effector during response execution (e.g., Heuer, 1995; Swinnen, 2002); however, some evidence suggests that the interference takes place, at least partly, at more abstract, conceptual level (see, Mechsner et al., 2001).

For example, Diedrichsen, Hazeltine, Kennerley, and Ivry (2001) examined how the stimuli used to cue the movements affected bimanual crosstalk. They found that when the movements were cued “directly” (i.e., with the presentation of stimuli at the appropriate endpoint of the movement) there was no evidence for bimanual crosstalk. The authors concluded that the cost associated with producing asymmetric movements with the two hands was associated with decoding symbolic cues into motor responses. That is, the crosstalk was located in central processes.

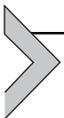
Hazeltine (2005) followed up on these findings with discrete button-press tasks and showed that RT depended on the relationship between the conceptual codes associated with the two responses rather than specific stimulus or response properties. The same two S-R alternatives could be compatible or incompatible, as indicated by performance measures, depending on how they were conceptualized. If participants were encouraged to think of their responses as differing in terms of distance from the body’s midline, then making innermost or outermost responses with both hands was performed more quickly than making leftmost or rightmost responses with both hands. However, if participants were encouraged to think of the responses as differing along the left–right axis, then the opposite pattern of results was obtained. Note that the critical stimuli were simple crosses presented at different spatial locations and the S-R mappings for these stimuli were the same, so the online interference associated with producing two responses is not just conceptual but that the concepts themselves are determined by the organization of the task. In short, response–response congruency is not based on stimuli or responses but the conceptualization of task.

This emphasis on rules rather than individual S-R associations echoes earlier work by Duncan (1977a, 1978), who also examined how individuals simultaneously selected button presses for each hand. Duncan (1977b) presented three main empirical findings: (1) RTs for consistent mappings were

shorter than RTs for inconsistent mappings; (2) there were repetition benefits when the rule repeated, even when the specific S-R association did not; and (3) errors generally reflected the application of the incorrect rule. As discussed previously, Duncan proposed the *spatial transformation model* of response selection, in which a transformation is applied to the stimulus to compute the response, but when the mapping is inconsistent a time-consuming, error-prone decision process must be invoked to determine which transformation to apply.

Duncan (1978) argued against models of response selection that produce a single S-R association, at least with tasks in which spatial transformations can be performed (see Halvorson & Hazeltine, 2015; for evidence that spatial transformation may be a special case). He noted that the idea that selection relies on rules rather than individual S-R associations is not new, citing Welford (1958), Shaffer (1965), and Rabbitt and Vyas (1973), but that most accounts of response selection emphasize S-R associations.

In sum, along with findings from experiments examining within-task congruency, studies of between-task congruency indicate that the selection of responses involves the activation of representations that include more than just stimulus and response information. Rather, abstract rules appear to play a critical role in determining how relevant and irrelevant information impinges on response selection. The notion of an S-R association provides little insight into how the congruency effects described here might emerge.



## 6. DUAL-TASK PERFORMANCE

While the studies of compatibility and congruency examine how activated stimulus and response information affects the selection of a single response, dual-task studies examine how ongoing processes for temporally overlapping tasks interfere with each other. In essence, this domain is closely related to the between-task congruency work, although the relationship is seldom explored (but see, Hazeltine, Diedrichsen, Kennerley, & Ivry, 2003; Hazeltine, Teague, & Ivry, 2002; Huestegge & Koch, 2010; Ivry, Franz, Kingstone, & Johnston, 1998; Ivry & Hazeltine, 2000; Navon & Miller, 1987). Dual-task experiments tend to use tasks that appear unrelated (e.g., responding manually to colored shapes and vocally to tones) and to not consider differences between specific combinations of stimuli across the two tasks. A central finding in dual-task research is that performing two tasks in

an overlapping fashion almost always produces performance costs on at least one of the tasks, even when they involve distinct stimulus and response modalities.

## 6.1 Single-Channel Models

The dominant theoretical accounts of this cost posit a single, central processor, with access to all sensory and motor systems, that intervenes between stimulus processing and response production (e.g., [Anderson et al., 2004](#); [Anderson, Taatgen, & Byrne, 2005](#); [Dux, Ivanoff, Asplund, & Marois, 2006](#); [Lien & Proctor, 2002](#); [McCann & Johnston, 1992](#); [Pashler, 1994b](#); [Pashler & Johnston, 1989](#)). The idea is that only a single S-R association can be activated at a time so when two stimuli are categorized at nearly the same time, the next processing stage, response selection, must be delayed for one of the categorized stimuli, and a dual-task cost is observed. However, it should be emphasized that the assertion that response selection is mediated by S-R associations and the assertion that response selection is limited to a single task at a time are independent, and accepting one claim requires no commitment to the other. In short, the single-channel account holds that there is a bottleneck at response selection; response selection can only be engaged for a single task at a time, so whenever it is simultaneously required by two tasks, processing for one of them is deferred. What this has to do with S-R associations we address later in this section.

The single-channel account addresses some of the vexing problems faced by models of response selection. By assuming that there is a unified central processor, such accounts can explain how we are able to map any stimulus to any response. Without a single, central response selection mechanism, it is difficult to envision, within the S-R association framework, how a range of perceptual codes can interface with a range of response systems, and how processing is controlled (although the proposition that response selection is restricted to one task at a time can be accepted without positing a single processor that selects all responses; see, [Pashler, 1994a](#)). Moreover, the notion of a single processor accounts for why dual-task costs are observed regardless of the modalities of the stimuli and responses ([Pashler, 1989, 1990](#); [Smith, 1967](#); [Welford, 1952, 1967](#)), and phenomenologically, it fits with our sense that we are able to think of only a single thing at any given moment.

However, this approach may introduce as many problems as it solves. How does a single mechanism operate on such diverse sets of inputs and outputs flexibly and with little or no practice? Can such a set of processes spanning so many inputs and outputs be meaningfully described and

investigated as a single system? And how does this account accommodate findings that suggest irrelevant stimulus information is translated into response codes in parallel with the relevant stimulus information (see, Eriksen & Schultz, 1979; Hommel, 1998; Lien & Proctor, 2002)?

Neuroimaging studies have been brought to bear on whether a single mechanism subserves response selection and the data are mixed. Some neuroimaging studies directly investigate dual-task performance by comparing single-task conditions to dual-task conditions (e.g., Klingberg, 1998; Szameitat, Schubert, Müller, & von Cramon, 2002) or conditions in which the tasks are separated by a long interval to conditions in which the tasks are separated by a short interval (e.g., Dux et al., 2006; Herath, Klingberg, Young, Amunts, & Roland, 2001). The typical finding in such experiments is that regions in the prefrontal cortex, often within the inferior frontal gyrus, are more active when two tasks must be performed close together in time (but see, Dux et al., 2006; Jiang, Saxe, & Kanwisher, 2004). However, these results may have as much to do with executive control processes that coordinate task performance than with the central processes that mediate response selection itself (see, Buss, Wifall, Hazeltine, & Spencer, 2014; Dux et al., 2006).

An alternative approach that avoids this interpretive issue is to manipulate the duration of central processes and determine whether the neural regions sensitive to this manipulation depend on the types of stimuli and responses used (for a hybrid approach, see Stelzel, Schumacher, Schubert, & D'Esposito, 2006). This procedure has often produced results that suggest that neural regions associated with central operations are contingent on the modalities of the stimuli (e.g., Schumacher & D'Esposito, 2002; Schumacher et al., 2003), although there have been findings suggesting a single processor that operates across multiple domains (e.g., Jiang & Kanwisher, 2003a,b). For example, in a neuroimaging study examining congruency effects, Schumacher, Schwarb, Lightman, and Hazeltine (2011) observed that the differences between incongruent and congruent trials depended on the modality of the stimuli. That is, incongruent auditory temporal flankers (i.e., the flankers preceded the target) increased activation compared to congruent auditory flankers in a set of regions that was mostly distinct from those that were sensitive to whether visual temporal flankers were congruent or not. In short, the evidence from the neuroimaging literature that response selection engages a single, common processor is weak.

Behavioral studies have sought to test the assumption that dual-task performance is limited by an immutable response selection bottleneck shared

by unrelated tasks. There are many results consistent with this idea (e.g., McCann & Johnston, 1992; Pashler, 1984, 1994a; Pashler & Johnston, 1989). However, support for a response selection bottleneck has been undermined by work investigating dual-task costs with moderate practice (Hazeltine et al., 2002; Schumacher, Seymour, Glass, Kieras, & Meyer, 2001). These studies paired visual stimuli with manual responses and auditory stimuli with vocal responses. Both studies reported the disappearance (or substantial reduction) in dual-task costs with increased practice. This may suggest that dual-task interference is caused not by a bottleneck in response selection but by strategic factors or crosstalk between codes associated with the two tasks. If this is the case, then it is another indication of both the conceptual and structural limitation in the simple S-R association account. However, there are alternate interpretations of these results that attempt to save the idea of a bottleneck in response selection (e.g., Anderson et al., 2005; Dux et al., 2009; Ruthruff, Johnston, & Van Selst, 2001) so these data are not dispositive for the nature of response selection.

While much of the behavioral work on dual-task performance has focused on visual-manual tasks paired with auditory-vocal tasks to avoid peripheral interference, there is evidence that the stimulus and response modalities do matter, outside of their indirect effects on task difficulty. Hazeltine, Ruthruff, and Remington (2006) compared dual-task performance on two task pairings (see also, Hazeltine & Ruthruff, 2006; Hazeltine & Wifall, 2011). One group of participants performed a visual-manual task (i.e., visually presented words mapped to manual button presses) and an auditory-vocal task (i.e., auditory tones mapped to spoken words) and another group of participants performed a visual-vocal task (i.e., visual words mapped to spoken words) and an auditory-manual task (i.e., tones mapped to button presses). Dual-task costs were much larger for the participants performing the visual-vocal and auditory-manual tasks, even when single-task RTs were equated, a finding that is particularly striking when one considers that on dual-task trials both groups of participants are seeing a word and hearing a tone, and pressing a button and saying a word. This finding indicates that interactions between ongoing central processes for two tasks depend on the task structure, not just the individual stimuli and responses. The difference in costs persisted across 16 sessions of practice, which is difficult to explain if one assumes that selection is mediated by S-R associations (an example of the conceptual limitation). Why should some associations interfere with each other more than others, given that the stimuli and responses were highly similar

across the two conditions, unless contextual information was also encoded in the task representation?

## 6.2 Crosstalk

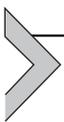
One explanation for these modality-dependent effects is crosstalk (i.e., interference between S-R associations for each task). That is, the amount of crosstalk between the two tasks may depend on their composition. Evidence for the idea that crosstalk provides a critical limitation on dual-task performance, rather than a unitary response selection mechanism, was reported by [Halvorson, Ebner, and Hazeltine \(2013\)](#), who investigated the near absence of dual-task costs across various combinations of tasks. The researchers were examining the claim that dual-task costs are dramatically reduced when tasks are ideomotor-compatible. The term ideomotor-compatible refers to tasks in which the relevant stimulus is highly similar to the consequences of the response. For example, saying the word “dog” to the auditory presentation of the word “dog” is ideomotor-compatible because the sensory consequences of saying the word “dog” are highly similar to the auditory stimulus “dog.” [Greenwald \(1970, 1972\)](#) proposed that such tasks do not require the central processes that are engaged by other tasks and thus are not subject to the same capacity limitations. However, [Halvorson, Ebner et al. \(2013\)](#) showed that a single ideomotor-compatible task was not sufficient to nearly eliminate dual-task costs. Thus, the authors argued that dual-task costs do not appear to be avoided because particular S-R associations do not require central processes. Rather, dual-task costs are avoided because the central processes for the two tasks involve codes that are not confusable (see also, [Navon & Miller, 1987](#)).

This proposal was further tested by [Halvorson and Hazeltine \(2015\)](#), who pitted two accounts of why pairs of ideomotor tasks do not produce dual-task costs. According to the ideomotor account, tasks in which the stimulus overlaps with the environmental consequences of the response bypass response selection processes so that there are no capacity limitations. According to the crosstalk account, dual-task costs result from crosstalk between simultaneously active codes associated with S-R translation. When a purely spatial task is paired with a purely verbal task, there is no crosstalk between the codes and no costs are observed. To determine which explanation provided the better account of dual-task costs, the researchers reversed the mapping of an ideomotor task so that there was still a purely spatial task paired with a purely verbal task, but the environmental

consequences of the responses no longer overlapped with the corresponding stimulus cues. These new task pairings produced no dual-task costs, indicating that ideomotor compatibility was not necessary to eliminate costs and that crosstalk was the more likely source. In this way, the findings indicate that the specific content of the central processes determines the magnitude of the dual-task interference, not just the generic activation of S-R associations (see also, [Hazeltine et al., 2006](#)). Under some circumstances, responses can be selected simultaneously with little cost.

The crosstalk account may be related to the between-task congruency effects described above. However, unlike dual-task costs, which are observed regardless of the particular stimuli that appear on the two tasks, between-task congruency effects do not involve specific combinations of stimuli/responses across the two tasks. Nonetheless, the underlying mechanism between the two phenomena may be the same. In other words, executive control may delay central processes on one task, resulting in generic dual-task costs, so that item-specific interactions between central processes do not occur (cf., [Meyer & Kieras, 1997a,b](#)). Alternatively, each of the items for one of the tasks may produce similar interference with each of the items for the other task, even though the magnitude of the interference is determined by the particular combination of items on each task; the items for one task would produce different amounts of interference when paired with the items for another task.

In any case, dual-task studies indicate that interference between concurrently performed tasks is content-specific (see, [Hazeltine et al., 2006](#)). That is, while costs are difficult to avoid, their magnitude depends on the relationship between the tasks. Such a state of affairs is not entirely inconsistent with models of response selection based on S-R associations, but there is presently no principled explanation for why any two particular S-R associations should interfere with each other more than any other pair. That different costs can be observed depending on how the same two stimuli are paired with the same two responses indicates that central codes containing more than just stimulus and response information must be considered in accounts of response selection.



---

## 7. TASK CONFIGURATION

Studies of dual-task performance indicate that behavioral costs depend on the structure of the tasks rather than simply the stimuli that need to be

identified and the responses that need to be produced. The importance of task structure is also apparent in studies examining how the selection of a response on one trial affects response selection on a subsequent trial. That is, while dual-task studies investigate how concurrently performed central processes interact, studies of task configuration probe how the selection of a response at one point in time affects the selection of responses at future points in time. This description suggests that the behavioral effects examined in studies of task configuration may be learning phenomena, and indeed task configuration and learning may be closely related (see, [Botvinick, 2007](#); [Verguts & Notebaert, 2008](#)), but for the present purposes, we make a distinction between effects that stem from the performance of a single, identifiable trial, as is typically the case in studies of task configuration, and effects that stem from the performance of multiple, possibly heterogeneous trials, as in most studies of practice and learning.

## 7.1 Cross-Trial Control

Changes in the configuration of task operations are the purview of cognitive control processes. For example, it is widely assumed that cognitive control is invoked to limit the influence of task-irrelevant information (e.g., [Botvinick et al., 2001](#); [Duncan, 2001](#); [Egner & Hirsch, 2005](#); [Logan & Gordon, 2001](#); [Norman & Shallice, 1986](#)), and evidence for the dynamic nature of these control processes can be found in studies demonstrating that resolving conflict on one trial can affect sensitivity to conflict on the subsequent trial. [Gratton, Coles, and Donchin \(1992\)](#) examined the congruency effect in the flanker task and found that its magnitude on one trial depended on the congruency of the previous trial. On trials in which the immediately previous trial was congruent, the flanker effect was larger than on trials in which the immediately previous trial was incongruent. This basic phenomenon is observed across a range of tasks used to study response competition, including the flanker task (e.g., [Akçay & Hazeltine, 2007](#)), the Simon task (e.g., [Hazeltine, Akçay, et al., 2011](#)) and the Stroop task (e.g., [Freitas, Bahar, Yang, & Banai, 2007](#)), and has been called conflict adaptation (e.g., [Ullsperger, Bylsma, & Botvinick, 2005](#)), the Gratton Effect (e.g., [Notebaert & Verguts, 2008](#)), sequential modulations (e.g., [Hazeltine, Lightman, Schwarb, & Schumacher, 2011](#)) and the congruency sequence effect (CSE, e.g., [Schmidt & Weissman, 2014](#)).

Because this phenomenon, which we will call CSE, presumably reflects changes in response selection processes, it can be used to probe their structure. Thus, there is extensive debate regarding the boundaries of the

CSE; that is, researchers have examined what features consecutive trials need to share in order for the congruency of one trial to affect the magnitude of the congruency effect on the next? Much of the existing work on this question has focused on the role of stimulus properties. For example, [Funes, Lupiáñez, and Humphreys \(2010\)](#) observed that the CSE did not occur when consecutive trials involved Simon and flanker conflict or vice versa (see also, [Blais, Robidoux, Risko, & Besner, 2007](#); [Egner, Delano, & Hirsch, 2007](#); [Egner & Hirsch, 2005](#); [Notebaert & Verguts, 2008](#)), and therefore concluded that control processes operated on specific stimulus dimensions (but see, [Fernandez-Duque & Knight, 2008](#); [Freitas et al., 2007](#)).

However, as with the studies of compatibility and congruency, there is evidence that the source of the effect is more abstract and conceptual than physical stimulus features or dimensions. [Hazeltine et al. \(2011\)](#) used a temporal flanker task (i.e., the flankers preceded the target) in which stimuli were presented either visually or aurally and observed that, under the appropriate conditions, CSE were observed when the stimuli changed from one modality to another. Because shared stimulus features appeared to play little role in whether the congruency of one trial affected the magnitude of the congruency effect on the next, the researchers proposed that CSE are not constrained by hard boundaries based on the organization of the perceptuo-motor system but rather are determined by the individual's representation of the task; CSEs depend on the extent to which consecutive trials belong to the same task. In short, Hazeltine and colleagues proposed the patterns of CSE reflected the structure of central processes rather than perceptual or attentional mechanisms (see also, [Akçay & Hazeltine, 2008, 2011](#); [Hazeltine, Akçay, et al., 2011](#)). This is similar to an episodic account proposed by [Spapé and Hommel \(2008\)](#), which holds that control settings are retrieved based on the episodic context. However, the task-set representation account emphasizes that factors beyond stimulus information can affect the magnitude of the CSE. That is, the similarity of consecutive trials relative to the similarity of other possible trials might affect the CSE, not just whether individual stimulus or response features overlap. Thus, the absence of CSE may reflect the active representation of distinct sets rather than a failure of retrieval processes. There is an obvious parallel here to the congruency and dual-task work described above: interactions between various sources of task-related information appear to incorporate aspects of the task goals and task structure, not just surface features of the stimuli and responses.

## 7.2 Partial Task Precuing

A second form of control relevant to the question of how task representations are structured can be observed in precuing tasks in which participants are given partial information about the upcoming stimulus that will signal a choice response. This situation, in which some aspects of the upcoming stimulus or response are cued, differs from the control studies described above in that the initial stimulus that influences subsequent performance is part of the same trial, does not require an overt response, and is (explicitly) informative. Nonetheless, the results of such studies can reveal much about the structure of central processes.

Rosenbaum (1980, 1983) demonstrated that when the possible responses were signaled by stimuli specifying particular movement parameters (e.g., which hand was to make the movement or the direction of the movement), not all precues provided the same benefits in performance, even when they provided equivalent reductions in the number of possible stimuli and responses (but see, Goodman & Kelso, 1980). For example, a precue indicating that the appropriate response would be one of the four involving the left hand produced greater reductions in RT than a precue indicating that it would be one of the four upward movements. Such an apparent violation of HHL (see Section 3) would not be obtained if the underlying selection process was simply an unorganized set of S-R associations a subset of which were primed by the precue. Thus, this result is another example of the boundaries between various components of the task representation; more information must be encoded into the task than simple S-R associations.

Rosenbaum attributed this effect to the organization of the motor system (see also, Miller, 1982). However, Reeve and Proctor (1984) showed that the configuration of the hands partly determined what precue information produced the largest decrements in RT, suggesting that the precue shortened central processes involved in response selection rather than peripheral motor programming processes. The debate persisted (e.g., Miller, 1985; Reeve & Proctor, 1985, 1990), in part because different patterns of advantages were obtained depending on the stimuli used and the configuration of the hands and response buttons. Adam, Hommel, and Umiltà (2003) manipulated the locations of the stimuli and locations of the responses independently and showed that these two factors along with the type of precue produced a three-way interaction. Critically, the type of precue that was most effective (i.e., produced the largest decrements in RT) depended on

the relationship between the stimuli and the responses. These findings indicate that the ability of individuals to use precues to prepare upcoming responses depends on the particular S-R mapping rather than organization of the stimuli or the motor system. Therefore, precuing effects reflect central processes.

In sum, these studies of cognitive control indicate that task set representation plays a critical role in performance. The selection of responses based on stimulus information affects the immediately subsequent selection of response in a way that depends on the relationships of both the stimuli and responses of the two selections. This indicates that the relevant control processes are operating on representations that include both stimulus and response information. Similarly, when a cue indicates that a subset of the possible stimuli will be presented, the reduction in RT is contingent on structure of the task. Conceiving of tasks as collections of S-R associations provides little headway for explaining how control processes change central processes in anticipation of upcoming events.



---

## 8. LEARNING AND PRACTICE

Dual-task studies indicate that task representation plays a critical role in determining the magnitude of dual-task costs; that is, they govern the way concurrently performed tasks interact. The same is true of the task configuration studies, although these describe interactions between events separated by short intervals of time. However, aggregations of trials can affect the performance of subsequent trials across larger timescales. Although we have emphasized the ability for humans to perform arbitrary S-R mappings with minimal practice, well-learned behaviors, which are often described as becoming effortless because they are encoded as automatic S-R associations (e.g., [Hommel, 2000](#); [Lien & Proctor, 2002](#); [Logan, 1988](#); [Schneider, 1985](#)), are actually complex and manifold.

### 8.1 Nonhuman Animal Learning

An obvious starting point for a discussion of the learning literature is conditioning. [Rescorla's \(1988b\)](#) review of the conditioning literature emphasizes that conditioning is generally mischaracterized as the formation of associations between stimuli and responses when in fact it is something much more complex (see also, [Rescorla, 1988a](#); [Rescorla & Wagner, 1972](#)). In short, instead of establishing links between stimuli and responses,

conditioning might be better described as reconciling the organism's internal model of the external world with the true state of the external world.

Rescorla (1988b) identifies several key findings to illustrate this point. First and most fundamentally, a conditioned stimulus will only elicit a particular response under certain circumstances; it is not the case that a stimulus always automatically produces a learned response. For example, an animal will not press a button to receive food when a light is presented if the animal is not hungry. This basic point illustrates that the animal hasn't learned an automatic association between the light and the button press but instead has learned a set of relationships among the light, the lever, and the outcome. Second, it is not just the co-occurrence of the unconditioned stimulus and the conditioned stimulus that leads to learning, but how predictive the unconditioned stimulus is of the conditioned stimulus; the base-rate of the unconditioned stimulus is critical. Moreover, stimuli can also be prevented from forming associations with an unconditioned stimulus if associations already exist between that unconditioned stimulus and another stimulus, a phenomenon known as blocking (Kamin, 1968). For example, an animal that has been trained to associate a light with food will salivate to the light. But if the light and a tone are then paired together before food is presented, the animal will not learn to salivate to the tone—even if it is as predictive of food as the light is.

Third, different conditioned stimuli will produce dramatically different responses, even when paired with the same unconditioned stimulus. An example of this is the Garcia Effect, which describes the fact that some conditioned stimuli (e.g., tastes) are more easily associated with particular unconditioned stimuli (e.g., sickness) than other conditioned stimuli (e.g., lights and sickness; Garcia & Koelling, 1966). Similarly, Rescorla (1988b) points out that different conditioned stimuli will evoke different behaviors when paired with the same unconditioned stimuli. For example, visual stimuli will typically elicit pecking behavior in pigeons when paired with food, whereas a diffuse tone will elicit increases in general activity (see also, Pinel & Treit, 1979).

These differences should not imply that the physical properties of the stimuli are solely responsible for driving learning. It has also been shown that competition between stimulus categories, rather than the individual stimuli, can produce overshadowing (Soto & Wasserman, 2012). That is, items that provide redundant information will interfere with category learning if they belong to the same category but not if they belong to varied categories. These findings point to another conceptual limitation in the

simple S-R association account of learning. They indicate that the learning is more abstract than simply pairing a particular stimulus with a particular response. Instead, they suggest the animal is building a complex model of the world that can be used for goal-based behavior. Finally, second-order conditioning (in which stimuli gain the ability to reinforce behavior through prior conditioning; see, [Rescorla, 1972](#)) also indicates the complexity of what is learned during conditioning.

While the above phenomena emphasize the conceptual nature of conditioning, there is also evidence for hierarchical structure within conditioned learning. [Rescorla \(1988b\)](#) notes that compound stimuli can be represented as distinct from either of component stimuli. Second-order conditioning procedures show that animals are able to represent compound stimuli (e.g., red horizontal bars) and use them as associates distinct from either component alone (e.g., red bars or horizontal bars). Animals are also able to use “occasion-setting” stimuli to cue positive or negative relations between other stimuli rather than to cue the occurrence of a particular stimulus ([Holland, 1983](#)). In this sense, the occasion-setting stimulus acts much like a task cue, indicating relationships among other stimuli that are independent of the relationships between those other stimuli and the occasion-setting stimulus itself. Thus, a stimulus can signal relationships between other stimuli independently of its associations with these other stimuli, indicating that the associations appear to be hierarchically organized and not restricted to linking individual events.

## 8.2 Human Learning and Practice

Studies of human learning have borrowed the concept of the S-R association from the animal learning literature to explain how stimulus information is efficiently transformed into motor activity. However, if the notion of a simple S-R association is insufficient to capture nonhuman animal behavior in constrained conditioning procedures, it would seem to provide a poor foundation for more complex human behaviors. There are examples in the cognitive literature that make this point explicitly. [Mayr and Bryck \(2005\)](#), for instance, demonstrated that the learning of S-R alternatives includes more than just the particular stimulus and particular response. In their experiments, the frequency of the S-R pairs was held constant but the S-R rules varied. The more frequently applied S-R rules showed greater learning than less frequently applied S-R rules, indicating that the abstract rule was incorporated in the sequence or that the learning was embedded in a rule-specific process.

There are parallels to the [Mayr and Bryck \(2005\)](#) findings in the serial reaction time (SRT) task literature. The SRT task is a popular means of examining motor learning (e.g., [Berns, Cohen, & Mintun, 1997](#); [Doyon et al., 1997](#); [Frensch, Buchner, & Lin, 1994](#); [Grafton, Hazeltine, & Ivry, 1995](#); [Hazeltine, Grafton, & Ivry, 1997](#); [Hazeltine & Ivry, 2002](#); [Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003](#); [Nissen & Bullemer, 1987](#); [Rauch et al., 1995](#); [Schumacher & Schwarb, 2009](#); [Schwarb & Schumacher, 2012](#); [Seidler et al., 2002](#); [Toni, Krams, Turner, & Passingham, 1998](#); [Willingham, Nissen, & Bullemer, 1989](#)), and several studies indicate that learning involves codes that are more than just stimuli and responses. [Schwarb and Schumacher \(2010\)](#) showed that learning depends on the relationship between the S-R alternatives (i.e., involves response selection; also see, [Schwarb & Schumacher, 2009](#)) and not on the specific features in the stimuli and responses. [Willingham and colleagues \(Willingham, 1998; Willingham, Wells, Farrell, & Stemwedel, 2000\)](#) proposed that learning in the SRT task was based on abstract locations that could be accessed by distinct effectors and scaled according to the task demands (see also, [Grafton, Hazeltine, & Ivry, 1998](#); [Keele, Jennings, Jones, Caulton, & Cohen, 1995](#); [Wright, 1990](#)). [Hazeltine \(2002\)](#) examined how practicing a motor sequence would transfer to novel sets of stimuli and novel responses. In this study, responses evoked specific tones, and transfer was best when the practiced and novel movements produced the same sequence of tones, even when both the stimuli and responses were novel. [Hazeltine \(2002\)](#) concluded that learned sequence representations included distal effects (see also, [Elsner & Hommel, 2001](#); [Ziessler & Nattkemper, 2001, 2002](#)), consistent with the claim that goal states, rather than just S-R associations, are part of the task set representation.

The transfer studies indicate that learning in the SRT task can include conceptual information, but there is also evidence that task structure can shape learning. [Schumacher and Schwarb \(2009\)](#) showed that sequences of responses were better learned when the interval between the sequenced task and the random, distractor task was increased. This finding may reflect that separating the tasks in time may eliminate interference in central response selection processes allowing for associations to be formed among the separate events. It is also possible that the longer interval provides a cue to subjectively organize the tasks. [Halvorson, Wagschal, and Hazeltine \(2013\)](#) used an instructional manipulation in which two groups of participants were encouraged to either consider two alternating sets of S-R mappings as belonging to the same task or different tasks. After a pretraining period that differed for the two groups, a training phase that was identical

for both groups was performed in which the stimuli for one of the S-R sets followed a repeating sequence. The group that was encouraged to conceptualize their actions as belonging to two separate tasks showed significantly more sequence learning than the group that conceptualized the two S-R sets as related. The authors argued that the task representation influenced the encoding of relationships between stimuli and could serve to protect learning from random, irrelevant stimuli.

Along these lines, [Freedberg, Wagschal, and Hazeltine \(2014\)](#) used a chord-learning task in which participants made two simultaneous responses and showed that the conceptual-relatedness of the stimuli and responses, rather than their modalities, determined whether practiced combinations were performed more quickly than novel combinations after practice. In other words, simultaneous responses are coded as a single action only when they were conceptually related. This finding points to both the conceptual and structural limitations of the S-R association account response selection. Not only is conceptual information encoded in the task set representation, but that information affects whether responses are encoded as related or unrelated.

While these studies demonstrate that task representations may affect the way that discrete actions are linked together, there is also evidence that motor adaptation may be sensitive to the way the task is conceptualized. [Taylor and Ivry \(2013\)](#) examined how motor adaptation to rightward movements transferred to leftward movements and discovered that the configuration of target locations determined whether the adaptation was rotational or translational, not whether the perturbation was rotational or translational. That is, participants learned a rotational adaptation if the target locations were arranged in a circle even if the perturbation was translational. The authors concluded that adaptation was not confined to low-level representations of the movement; instead, it appears that the task representation plays a critical role.

It has been proposed that as a task becomes highly practiced, behavior ceases to be driven by more complex verbal codes and instead is based on more automatically activated S-R associations (e.g., [Anderson, 1982](#); [Logan, 1988](#); [Pashler & Baylis, 1991](#)). However, while there is evidence central processes become more efficient with practice (e.g., [Anderson et al., 2005](#); [Dux et al., 2009](#); [Reisberg, Baron, & Kemler, 1980](#); [Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003](#)), there is little evidence for the formation of direct links between stimulus and response codes. Rather, across a wide array of task procedures, complex contextual information appears to

be encoded into the task set representation, and these contextual effects lead to a diverse set of behavioral consequences. In sum, learning occurs at multiple levels of representation and captures a diverse array of relationships between task components. Nonetheless, even in cases of nonhuman animal learning and motor adaptation, there is evidence that the encoded information includes more than simple S-R associations.



## 9. MEMORY

Thus far, we have outlined the conceptual and structural limitations in the traditional S-R association account of response selection. We have shown how this account fails to explain a wide range of fundamental effects relating to human and animal performance. Another area where the S-R association account also fails to account for the data is memory retrieval.

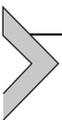
### 9.1 Priming

There may not be a more direct case for S-R associations than priming. Priming is thought to occur directly from spreading activation across associations in memory (e.g., Logan, 1990; Meyer & Schvaneveldt, 1971). However, even in this case, the data suggest that more than S-R associations matter. Priming has been shown to occur at an abstract conceptual level that is superordinate to the stimuli and responses used in the task. For example, Horner and Henson (2009) found reduced priming to stimuli in a repetition priming procedure when the classification of the stimuli changed (e.g., bigger to smaller and vice versa) from one trial to the next and also when the response changed from vocal to manual. That is, the same stimuli and response systems were used but priming depended on the higher-order associations between the S-R pairs. These results suggest that priming does not only activate a stimulus representation, but that aspects of the entire task set are primed—and when aspects of the task set change, priming is reduced. As reviewed by Henson et al. (2014), priming occurs across many dimensions of the S-R pair. They propose that “SR bindings are more than simple associations between a specific concept and motor act: they are complex, structured representations that simultaneously bind multiple levels of stimulus, response and task representation (p. 382).” This characterization is clearly in line with our conclusions from the congruency, dual-task, control, and learning literature and could serve as a succinct description of the task sets that support central processes.

## 9.2 Explicit Memory

There are other possible effects of task sets in the memory literature as well. Consider release from proactive interference (Wickens, Born, & Allen, 1963), which is observed when participants attempt to store a number of items in working memory across a series of trials. The items come from the same category (e.g., animals) for a few trials then change to a new category (e.g., furniture). Participants' memory performance decays across trials within a category (due to proactive interference; Keppel & Underwood, 1962) but improves after a category switch. There are a number of proposed mechanisms to explain this release from proactive interference. For example, the change in category may affect attention, memory encoding or some combination of factors (Kintsch, 1970; Wickens, 1970, 1972). Any of these proposed mechanisms may be a consequence of a shift in task set. If participants develop a task set for the procedure that includes the category domain, then a shift in category may lead to the creation of a new task set. Consequently, the attention, memory and control processes working within the original task set no longer affect performance under the new set.

Task set representation may also explain the importance of *retrieval mode*. Retrieval mode is a hypothesized cognitive state in which people are oriented towards remembering existing knowledge (Tulving, 1983). This state improves the effectiveness of currently present stimuli to act as retrieval cues. Retrieval mode involves activating a task set for memory retrieval, so attention and memory processes are allocated to the appropriate stimuli and the associates in memory of those stimuli. The connection between retrieval mode and task set is amplified by findings showing the benefits of a related process of *retrieval orientation*. Retrieval orientation is, in essence, the task set adopted as individuals interpret retrieval cues (e.g., phonologically or spatially, Rugg, Allan, & Birch, 2000; Wilding, 1999). When these cues are interpreted appropriately, retrieval performance is better (for a review see, Rugg & Wilding, 2000). Thus, retrieval mode and orientation affect stimulus processing and change memory retrieval efficiency in much the same way that task sets organize and segregate response selection.



## 10. SUMMARY OF THE BEHAVIORAL PHENOMENA

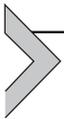
We have described a range of behavioral effects observed across disparate procedures and a common theme has emerged: Response selection relies on complex representations that incorporate more than simple S-R

associations. The task switching literature indicates that in many cases tasks appear to be represented as rules rather than sets of associations. Studies probing the source of the linear relationship between the  $\log_2$  of the number of S-R alternatives and RT, known as Hick–Hyman law, show that these alternatives are partitioned into task sets, so that only a very few of them impinge on response selection processes at a given time. Furthermore, stimuli associated with the same response can produce smaller increases in RT than stimuli associated with different responses, suggesting that the perceptual system does not simply activate an individual S-R association in a feedforward manner. The surprising complexity of S-R compatibility phenomena also emphasizes that S-R alternatives must be grouped and coded in a relational fashion. The S-R compatibility of a given alternative is determined in comparison to other possible alternatives rather than in terms of absolute stimulus and response properties. Both within-task and between-task congruency effects are consistent with the proposal that response selection processes employ representations that prioritize conceptual and relational information. The congruency of irrelevant stimulus or response information depends on its conceptual relationship to the selected action, not the irrelevant stimulus' or response's physical properties.

More complex behavioral phenomena involving control processes to coordinate task operations reinforce the need for task representations that are abstract and structured. When two tasks are performed concurrently, the magnitude of the dual-task interference depends on the structure of the tasks, not just the stimuli and responses presented and produced on a given trial. The importance of structure is also apparent in studies of task configuration. The ability to alter task operations based on changing expectations about the upcoming stimuli depends on the relationships among the S-R mappings, not just the relationships among stimuli or among responses. With regard to cross-trial cognitive control, this means that task representations determine whether the congruency of the previous trial modulates the magnitude of the congruency effect on the current trial. In other words, the modulation depends not just on the stimuli and responses of the two trials, but on whether the two trials are conceptualized as belonging to the same task. With regard to partial-task precuing, this means that the benefit of a precue depends not just on how the subset of stimuli indicated by the precue corresponds with the perceptual groupings of the stimuli or motor parameters of the corresponding responses, but also on an interaction between these two factors—that is, the benefit depends on how the information provided by the precue aligns with the structure of the task.

Finally, the importance of task structure can be observed at larger time scales, as it guides the learning of contingencies between simultaneous or consecutively performed actions. Note that in the nonhuman animal learning literature, there is strong evidence that learning is based on minimizing prediction error, not the formation of associations between stimuli and responses, and that these predictions can emerge from hierarchical representations. Furthermore, studies of human memory indicate that both priming and explicit retrieval are dependent on structured task representations.

In sum, inspection of these diverse behavioral domains consistently indicates that response selection is driven by task representations that involve more than simple S-R associations. The information guiding central processes is both conceptual and structured, as befits the intricacies of voluntary action.



---

## 11. TASK SET REPRESENTATION IN THE HUMAN BRAIN

Thus far, we have mostly discussed behavioral evidence for task set representations. Here we turn to a brief review of the neuroscience data for how task set representations may be instantiated in the brain. There are many proposed neural mechanisms for task sets. It has long been noted that the prefrontal cortex appears critical for flexible goal-based behavior (e.g., [Duncan, 1986](#); [Fuster, 1993](#); [Lhermitte, 1983](#); [Milner, 1963](#); [Shallice, 1982](#); [Stuss & Benson, 1984](#)), so much research has focused on how this region of the brain can coordinate processes in other regions to give rise to purposeful action. We turn to data from the prefrontal cortex for clues about the task representations that might augment or supplant S-R associations in theories of voluntary behavior.

### 11.1 Prefrontal Cortex

[Duncan \(2001\)](#) noted that experiments with human participants investigating working memory and attentional control across a variety of tasks produce activity in prefrontal cortex and proposed that the response properties of neurons in prefrontal cortex (especially dorsolateral, ventrolateral, and medial regions) change according to the task demands. Some evidence for this idea comes from the ubiquity of activation in human brain regions across tasks, but more direct evidence for this adaptive coding comes from experiments on nonhuman primates by [Miller and colleagues \(e.g., Miller,](#)

Nieder, Freedman, & Wallis, 2003; Wallis, Anderson, & Miller, 2001). They found that some neurons along the principal sulcus in the macaque prefrontal cortex responded to task-relevant stimuli regardless of their actual identities. For example, a neuron may respond to a picture of a cat and not a dog when the cat requires a response and it may respond to the dog and not the cat when the dog requires a response. Thus, these neurons adapt to the task demands, although it is unclear whether the change in this receptivity reflects the task set, the attentional demands, or other forms of abstract coding (see also, Siegel, Buschman, & Miller, 2015). Yet, it does account for the frequencies with which prefrontal activation is observed in human studies of working memory and response selection. Some possible clues about the functional properties of the receptive fields of prefrontal neurons have been reported by Rigotti and colleagues (Barak, Rigotti, & Fusi, 2013; Rigotti et al., 2013). They proposed that the mixed selectivity of prefrontal neurons might reflect high-dimensional representations that can support flexible, complex behavior.

A large body of work has focused on the role of the prefrontal cortex in cognitive control. For example, Miller and Cohen (2001) proposed that prefrontal cortex exerts control of a situation when multiple competing representations or responses are activated. The conflict signal arises in anterior cingulate and triggers a response in prefrontal regions to adjust attention, retrieve additional information from memory or exert control in some other way to resolve the conflict. Dosenbach, Fair, Cohen, Schlaggar, and Petersen (2008) argued that control consists of multiple local modules that are connected to one another by long-range connections and organized into two main brain networks (see also, Braver, 2012). The cingulate-operculum network (including dorsal anterior cingulate and anterior and ventral prefrontal cortex) mediates task-set maintenance. This network typically mediates processing changes relatively slowly (e.g., across experimental trials). In contrast, the frontal-parietal network (including dorsolateral prefrontal and superior parietal cortices) mediates the adjustment of top-down control based on rapidly changing environmental information (e.g., within an experimental trial).

Other accounts of control involve more elaborately structured task representations. For instance, Badre (2008) proposed that the control hierarchy in prefrontal cortex is built on increasingly abstract representations of task sets. In this model, the most caudal regions (i.e., premotor cortex) represent direct S-R mappings. More anterior regions represent more abstract relationships between representations. Dorsal prefrontal cortex

mediates processing when a conjunction of stimuli is required. Lateral prefrontal cortex mediates conflict/comparisons between dimensions or classes of stimuli. Anterior prefrontal cortex mediates comparisons between the context for when some set of stimulus features are task relevant or not. [Koechlin and Summerfield \(2007\)](#) proposed an alternative rostro-caudal model of prefrontal cortex organization (see also, [Christoff & Gabrieli, 2000](#)). Their cascade model postulates that control is implemented as a result of competition between representations at different levels of a control hierarchy. The lowest level of the hierarchy is premotor cortex. This region mediates sensory control (i.e., the S-R mappings). At the next level, dorsal prefrontal cortex mediates contextual control (i.e., selecting when particular S-R mappings should be applied over others). The next level is episodic control, which is mediated by lateral prefrontal cortex. Processing in this region overrides the current context with special case rules applicable to the current situation (episode). At the top of the control hierarchy is anterior prefrontal cortex. This region mediates branching control (i.e., maintaining not currently relevant task information for subsequent use). Finally, [O'Reilly \(2010\)](#) proposed that representations in prefrontal cortex change not only along the rostro-caudal dimension but also along the superior-inferior and lateral-medial dimensions. Common to these hierarchical theories is the idea that many aspects of the task and current situation are encoded (in different ways across prefrontal cortex). Although these models include S-R associations, responses are selected by a complex interplay of processes operating on multiple levels of representation that capture various components of the task.

## 11.2 Characterizing Control-Related Neural Activity

The complexity of these findings highlights the difficulty of interpreting neural data within the prefrontal cortex, given the many possible relationships between activation on various components of the task. In an influential review, [Sakai \(2008\)](#) proposed that brain regions mediating the representation of a task set should activate after a task cue and before a task stimulus (see also, [Dosenbach et al., 2008](#)). Regions with this activation profile are likely involved in the preparation for task performance (i.e., the instantiation of a task set), rather than the execution of information processing for task performance.

[Dosenbach et al. \(2006\)](#) sought to identify brain regions with this profile. They collected brain activation data from participants while they performed a variety of tasks. The tasks varied across stimulus modality

(visual, auditory), representation category (verbal, spatial), and response modality (manual, vocal). They found that three regions (anterior prefrontal cortex, dorsal anterior cingulate cortex/medial superior frontal cortex and anterior insula/frontal operculum) that were consistently active during preparation across nearly all of their tasks. Assuming that task set representations are amodal, then these are good candidate regions to support them. However, there may be modality-specific aspects of a task set that are not captured by this amodal brain activity.

These theories of how control is instantiated in the prefrontal cortex differ in terms of the composition of the underlying processes. Some propose hierarchical influences that depend on the type of conflict within task sets; others propose distinct neural representations for slow versus fast changes in task set representation, and still others propose a general framework for how brain systems are recruited to instantiate task sets. Yet, in every case, these theories propose that the prefrontal cortex encodes complex information that is conceptual and highly structured. Complex behavior involves an interaction between multiple-levels of information—not simply associations between stimuli and responses.



---

## 12. GENERAL COMMENTS

In this chapter, we have sampled over 80 years of research showing that response selection is implemented by a complex set of processes that operate on task-based parameters as opposed to simple S-R associations. Across a range of topics, the picture is consistent: low-level stimulus and response features play a subordinate role to more abstract aspects of the task in the generation of voluntary action. Given the flexibility and complexity of human behavior, controlling motor behavior based on conceptual, structured representations seems optimal for ensuring that goals are achieved.

The emphasis on the conceptual aspects of tasks facilitates successful navigation through the real world. Goal states, in contrast to stimulus and response properties, capture the critical invariances that are necessary to encode for adaptive behavior. Humans and other animals do not rely on vagaries of the environment to present stimuli that are consistently linked to particular appropriate behaviors. Rather, we initiate motor behavior based on the end-states that we are attempting to achieve (see, [Rosenbaum et al., 1990](#)). For this reason, actions appear to be coded in terms of the

expected outcomes rather than the underlying motor activations during selection (see, [Hommel et al., 2001](#); [Prinz, 1990](#)).

The need for structure arises from the complexity of the environment and the need for the animal to produce different responses to the same stimuli depending on the current circumstances and task demands. The same movements can be made in a variety of contexts to obtain a variety of outcomes. Moreover, actions that are performed close together in time may be less related (in terms of a common goal) than actions performed far apart in time (see, e.g., [Zacks & Swallow, 2007](#)). Therefore, it is necessary to organize action to capture meaningful relationships among events that can be used to guide behavior.

With these requirements in mind, it seems reasonable to ask what is gained by referring to simple S-R associations. On a functional level, the notion of an S-R association may be inescapable. Linking particular stimuli to particular responses essentially describes most tasks. It has also been argued that S-R associations provide a key contribution to behavior, but they require additional control processes to govern their implementation (e.g., [Cohen, Dunbar, & McClelland, 1990](#); [Lhermitte, 1983](#); [Miller & Cohen, 2001](#); [Norman & Shallice, 1986](#)). In this framework, abstract S-R associations that specify more than physical stimulus features and motor parameters are coupled with control processes that organize and activate them in a goal-based fashion. We are aware of no evidence that argues against this sort of approach.

Thus, we do not intend to argue that the concept necessarily be abandoned. Instead, our intention is two-fold. First, we aim to establish that theories should specify the level of representation for S-R associations, so that it is clear exactly what information forms the basis of the association. While it seems clear that in many cases the information is very abstract, the contents of such representations are most often not clearly explicated. It may be that the consideration of this issue will lead to accounts that are based on more structured associative mechanisms that are not reliant on a single level of connection mediating stimulus and response information.

Second, we pose the question of whether S-R associations are really necessary for accounts of voluntary behavior. Given the complexity of the control mechanisms already proposed, it seems possible that these processes operate on something other than S-R associations, possibly activating motor systems based on anticipated consequences. Such models would seem particularly apt for explaining novel actions, for which there should be no encoded S-R associations. If it is allowed that behavior might be driven

by control processes rather than S-R associations, then practice might tune these control processes instead of instantiating S-R associations to take their place (see, [Dux et al., 2009](#)). As reviewed above, there is evidence to indicate that practice makes response selection more efficient but does not obviate its role in behavior (e.g., [Dutta & Proctor, 1992](#); [Ruthruff et al., 2003](#); [Wifall, McMurray, & Hazeltine, 2014](#)).

One of the obstacles to eschewing the notion of S-R associations is that it is difficult to envision alternative frameworks. Nonetheless, given the available evidence, it seems worthwhile to consider workable options. How can we integrate the importance of context and intention into models of response selection without resorting to homuncular mechanisms that choose actions based on current goal states? It may be that statistical learning processes that take into account a wide array of information (e.g., [Ernst & Banks, 2002](#); [Fiser & Aslin, 2002](#); [Saffran, Aslin, & Newport, 1996](#)), perhaps in conjunction with the dopaminergic reward system (e.g., [Botvinick, Niv, & Barto, 2009](#); [Miller & Cohen, 2001](#)) and/or cognitive development (e.g., [Verbruggen, McLaren, & Chambers, 2014](#)), may be able to capture the complex patterns of behavior that we describe here. Alternatively, it might be possible to divide response selection into separate components none of which directly associate individual stimuli with responses or, at least, assign a privileged role to those associations. For example, one might conceive of two sets of processes, one based on minimizing prediction error of sensorimotor events (e.g., [Rescorla & Wagner, 1972](#); [Thompson, 1990](#)) and another based on maximizing reward (e.g., [Houk, Adams, & Barto, 1995](#); [Izawa & Shadmehr, 2011](#); [Schultz et al., 1995](#)), that act in tandem to guide behavior.

In conclusion, the evidence presented here shows that S-R associations, as traditionally conceived, contribute little to theories of voluntary behavior. Motor systems rely on sensory information, and sensory systems incorporate motor states. The two sets of processes are more fundamentally integrated—with each other and with contextual information—than implied by the notion of the single bridging connection of the S-R association (see, [Cisek & Kalaska, 2010](#); [Hommel et al., 2001](#); [Prinz, 1990](#)). The emphasis on S-R bindings may hobble our appreciation of the richness of central processes.

## ACKNOWLEDGMENTS

The authors wish to thank Matthew Bezddek, Savannah Cookson, Michael Freedberg, Christine Godwin, Susan Ravizza, and Derek Smith for their extremely helpful comments on earlier versions of this chapter.

## REFERENCES

- Adam, J. J., Hommel, B., & Umiltà, C. (2003). Preparing for perception and action (I): the role of grouping in the response-cuing paradigm. *Cognitive Psychology*, *46*, 302–358.
- Akçay, Ç., & Hazeltine, E. (2007). Feature-overlap and conflict monitoring: two sources of sequential modulations. *Psychonomic Bulletin and Review*, *14*, 742–748.
- Akçay, Ç., & Hazeltine, E. (2008). Conflict adaptation depends on task structure. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 958–973.
- Akçay, Ç., & Hazeltine, E. (2011). Domain-specific conflict adaptation without feature repetitions. *Psychonomic Bulletin and Review*, *18*, 505–511.
- Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: exploring the dynamic control of tasks. In C. Umiltà, & M. Moscovitch (Eds.), *Attention and performance: Vol. XV. Attention and performance* (pp. 421–452). Cambridge, MA: Harvard University Press.
- Anderson, J. R. (1976). *Language, memory, and thought*. Hillsdale, NJ: Erlbaum.
- Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review*, *89*, 369–406.
- Anderson, J. R., Bothell, D., Byrne, M. D., Douglass, S., Lebiere, C., & Qin, Y. (2004). An integrated theory of the mind. *Psychological Review*, *111*, 1036–1060.
- Anderson, J. R., Taatgen, N. A., & Byrne, M. D. (2005). Learning to achieve perfect time-sharing: architectural implications of hazeltine, teague, and ivry (2002). *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 749–761.
- Badre, D. (2008). Cognitive control, hierarchy, and the rostral-caudal organization of the frontal lobes. *Trends in Cognitive Sciences*, *12*(5), 193–200. <http://dx.doi.org/10.1016/j.tics.2008.02.004>.
- Barak, O., Rigotti, M., & Fusi, S. (2013). The sparseness of mixed selectivity neurons controls the generalization–discrimination trade-off. *Journal of Neuroscience*, *33*, 3844–3856.
- Berns, G. S., Cohen, J. D., & Mintun, M. A. (1997). Brain regions responsive to novelty in the absence of awareness. *Science*, *276*, 1272–1275.
- Blais, C., Robidoux, S., Risko, E. F., & Besner, D. (2007). Item-specific adaptation and the conflict-monitoring hypothesis: a computational model. *Psychological Review*, *114*, 1076–1086.
- Botvinick, M. M. (2007). Conflict monitoring and decision making: reconciling two perspectives on anterior cingulate function. *Cognitive, Affective and Behavioral Neuroscience*, *7*, 356–366.
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*, 624–652.
- Botvinick, M. M., Niv, Y., & Barto, A. C. (2009). Hierarchically organized behavior and its neural foundations: a reinforcement learning perspective. *Cognition*, *113*, 262–280.
- Brass, M., & Cramon, D. Y. (2004). Decomposing components of task preparation with functional magnetic resonance imaging. *Journal of Cognitive Neuroscience*, *16*, 609–620.
- Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends in Cognitive Sciences*, *16*, 106–113.
- Buss, A., Wifall, T., Hazeltine, E., & Spencer, J. P. (2014). Integrating the behavioral and neural dynamics of response selection in a dual-task paradigm: a dynamic neural field model of Dux et al. (2009). *Journal of Cognitive Neuroscience*, *26*, 334–351.
- Christoff, K., & Gabrieli, J. D. E. (2000). The frontopolar cortex and human cognition: evidence for a rostrocaudal hierarchical organization within the human prefrontal cortex. *Psychobiology*, *28*(2), 168–186.
- Cisek, P., & Kalaska, J. F. (2005). Neural correlates of reaching decisions in dorsal premotor cortex: specification of multiple direction choices and final selection of action. *Neuron*, *45*, 801–814.
- Cisek, P., & Kalaska, J. F. (2010). Neural mechanisms for interaction with a world full of action choices. *Annual Review of Neuroscience*, *33*, 269–298.

- Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychological Review*, *97*, 332–361.
- Coles, M. G. H., Gratton, G., Bashore, T. R., Eriksen, C. W., & Donchin, E. (1985). A psychophysiological investigation of the continuous flow model of human information-processing. *Journal of Experimental Psychology: Human Perception and Performance*, *11*, 529–553.
- De Jong, R., Liang, C.-C., & Lauber, E. J. (1994). Conditional and unconditional automaticity: a dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 731–750.
- Diedrichsen, J., Hazeltine, E., Kennerley, S., & Ivry, R. B. (2001). Absence of bimanual interference during directly-cued actions. *Psychological Science*, *12*, 493–498.
- Dosenbach, N. U. F., Fair, D. A., Cohen, A. L., Schlaggar, B. L., & Petersen, S. E. (2008). A dual-networks architecture of top-down control. *Trends in Cognitive Sciences*, *12*(3), 99–105. <http://dx.doi.org/10.1016/j.tics.2008.01.001>.
- Dosenbach, N. U. F., Visscher, K. M., Palmer, E. D., Miezin, F. M., Wenger, K. K., Kang, H. S. C., et al. (2006). A core system for the implementation of task sets. *Neuron*, *50*(5), 799–812. <http://dx.doi.org/10.1016/j.neuron.2006.04.031>.
- Doyon, J., Gaudreau, D., Laforce, R. J., Catronguay, M., Bedard, F., & Bouchard, J.-P. (1997). Role of striatum, cerebellum, and frontal lobes in the learning of a visuomotor sequence. *Brain and Cognition*, *34*, 218–245.
- Dreisbach, G., Goschke, T., & Haider, H. (2006). Implicit task sets in task switching. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *32*, 1221–1233.
- Dreisbach, G., Goschke, T., & Haider, H. (2007). The role of task rules and stimulus-response mappings in the task switching paradigm. *Psychological Research*, *71*, 383–392.
- Dreisbach, G., & Haider, H. (2008). That's what task sets are for: shielding against irrelevant information. *Psychological Research*, *72*, 355–361.
- Dreisbach, G., & Haider, H. (2009). How task representations guide attention: further evidence for the shielding function of task sets. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *35*, 477–486.
- Duncan, J. (1977a). Response selection errors in spatial choice reaction tasks. *Quarterly Journal of Experimental Psychology*, *29*, 415–423.
- Duncan, J. (1977b). Response selection rules in spatial choice reaction tasks. In S. Dornic (Ed.), *Attention and performance* (Vol. VI, pp. 49–61). Hillsdale, NJ: Erlbaum.
- Duncan, J. (1978). Response selection in spatial choice reaction: further evidence against associative models. *The Quarterly Journal of Experimental Psychology*, *30*, 429–440.
- Duncan, J. (1986). Disorganisation of behaviour after frontal lobe damage. *Cognitive Neuropsychology*, *3*, 271–290.
- Duncan, J. (2001). An adaptive coding model of neural function in prefrontal cortex. *Nature Reviews Neuroscience*, *2*(11), 820–829. <http://dx.doi.org/10.1038/35097575>.
- Duncan, J., & Owen, A. M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neuroscience*, *23*(10), 475–483.
- Dutta, A., & Proctor, R. W. (1992). Persistence of stimulus-response compatibility effects with extended practice. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *18*, 801–809.
- Dux, P. E., Ivanoff, J., Asplund, C. L., & Marois, R. (2006). Isolation of a central bottleneck of information processing with time-resolved fMRI. *Neuron*, *52*, 1109–1120.
- Dux, P. E., Tombu, M. N., Harrison, S., Rogers, B. P., Tong, F., & Marois, R. (2009). Training improves multitasking performance by increasing the speed of information processing in human prefrontal cortex. *Neuron*, *63*, 127–138.
- Egner, T., Delano, M., & Hirsch, J. (2007). Separate conflict-specific cognitive control mechanisms in the human brain. *NeuroImage*, *35*, 940–948.

- Egner, T., & Hirsch, J. (2005). Cognitive control mechanisms resolve conflict through cortical amplification of task-relevant information. *Nature Neuroscience*, *8*, 1784–1790.
- Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 229–240.
- Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception and Psychophysics*, *16*, 143–149.
- Eriksen, C. W., & Schultz, D. W. (1979). Information processing in visual search: a continuous flow conception and experimental results. *Perception and Psychophysics*, *25*, 249–263.
- Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, *415*, 429–433.
- Fernandez-Duque, D., & Knight, M. (2008). Cognitive control: dynamic, sustained, and voluntary influences. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 340–355.
- Fiser, J., & Aslin, R. N. (2002). Statistical learning of higher-order temporal structure from visual shape information. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *28*, 458–467.
- Fitts, P. M., & Deininger, R. L. (1954). S-R Compatibility: correspondence among paired elements within stimulus and response codes. *Journal of Experimental Psychology*, *48*, 483–492.
- Fitts, P. M., & Seeger, C. M. (1953). S-R compatibility: spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, *46*, 199–210.
- Franz, E. A., Eliassen, J. C., Ivry, R. B., & Gazzaniga, M. S. (1996). Dissociation of spatial and temporal coupling in the bimanual movements of callosotomy patients. *Psychological Science*, *7*, 306–310.
- Freedberg, M. V., Wagschal, T. T., & Hazeltine, E. (2014). Incidental learning and task boundaries. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *40*, 1680–1700.
- Freitas, A. L., Bahar, M., Yang, S., & Banai, R. (2007). Contextual adjustments in cognitive control across tasks. *Psychological Science*, *18*, 1040–1043.
- Frensch, P. A., Buchner, A., & Lin, J. (1994). Implicit learning of unique and ambiguous serial transactions in the presence and absence of a distractor task. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *20*, 567–584.
- Funes, M. J., Lupiáñez, J., & Humphreys, G. W. (2010). Analyzing the generality of conflict adaptation effects. *Journal of Experimental Psychology: Human Perception and Performance*, *36*, 147–161.
- Fuster, J. M. (1993). Frontal lobes. *Current Opinion in Neurobiology*, *3*, 160–165.
- Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (2002). Action representation and the inferior parietal lobule. In W. Prinz, & B. Hommel (Eds.), *Attention and performance* (Vol. XIX). Oxford: Oxford University Press.
- García, J., & Koelling, R. A. (1966). Relation of cue to consequence in avoidance learning. *Psychonomic Science*, *4*, 123–124.
- Gaskell, M. G., & Marslen-Wilson, W. D. (2002). Representation and competition in the perception of spoken words. *Cognitive Psychology*, *45*, 220–266.
- Goodman, D., & Kelso, J. A. (1980). Are movements prepared in parts? Not under compatible (naturalized) conditions. *Journal of Experimental Psychology: General*, *109*, 475–495.
- Grafton, S. T., Hazeltine, E., & Ivry, R. B. (1995). Functional mapping of sequence learning in normal humans. *Journal of Cognitive Neuroscience*, *7*, 497–510.
- Grafton, S. T., Hazeltine, E., & Ivry, R. B. (1998). Abstract and effector-specific representations of motor sequences identified with PET. *Journal of Neurophysiology*, *18*, 9420–9428.
- Gratton, G., Coles, M. G. H., & Donchin, O. (1992). Optimizing the use of information: strategic control of activation and responses. *Journal of Experimental Psychology: General*, *121*, 480–506.

- Greenwald, A. G. (1970). A choice reaction time test of ideomotor theory. *Journal of Experimental Psychology*, *86*, 20–25.
- Greenwald, A. G. (1972). On doing two things at once: time sharing as a function of ideomotor compatibility. *Journal of Experimental Psychology*, *94*, 52–57.
- Guiard, Y. (1983). The lateral coding of rotations: a study of the Simon effect with wheel-rotation responses. *Journal of Motor Behavior*, *15*, 331–342.
- Halvorson, K. M., Ebner, H., & Hazeltine, E. (2013). Investigating perfect time-sharing: the relationship between IM-compatible tasks and dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 527–545.
- Halvorson, K. M., & Hazeltine, E. (2015). Do small dual-task costs reflect ideomotor compatibility or the absence of crosstalk? *Psychonomic Bulletin and Review*. <http://dx.doi.org/10.3758/s13423-015-0813-8>.
- Halvorson, K. M., Wagschal, T. T., & Hazeltine, E. (2013). Conceptualization of task boundaries preserves implicit sequence learning under dual-task conditions. *Psychonomic Bulletin and Review*, *20*, 1005–1010.
- Hammond, N., & Barber, P. J. (1978). Evidence for abstract response codes: ear-hand correspondence effects in a three choice reaction-time task. *Quarterly Journal of Experimental Psychology*, *30*, 71–82.
- Hawkins, H. L., MacKay, S. L., Holley, S. L., Friedin, B. D., & Cohen, S. L. (1973). Locus of the relative frequency effect in choice reaction time. *Journal of Experimental Psychology*, *101*, 90–99.
- Hazeltine, E. (2002). The representational nature of sequence learning: evidence for goal-based codes. In W. Prinz, & B. Hommel (Eds.), *Attention and performance* (Vol. XIX, pp. 673–689). Oxford: University Press.
- Hazeltine, E. (2005). Response-response compatibility during bimanual movements: evidence for the conceptual coding of action. *Psychonomic Bulletin and Review*, *12*, 682–688.
- Hazeltine, E., Akçay, Ç., & Mordkoff, J. T. (2011a). Keeping Simon simple: examining the relationship between sequential modulations and feature repetitions with two stimuli, two locations, and two responses. *Acta Psychologica*, *136*, 245–252.
- Hazeltine, E., Diedrichsen, J., Kennerley, S., & Ivry, R. B. (2003). Bimanual cross-talk during reaching movements is primarily related to response selection, not the specification of motor parameters. *Psychological Research*, *67*, 56–70.
- Hazeltine, E., Grafton, S. T., & Ivry, R. B. (1997). Attention and stimulus characteristics determine the locus of motor sequence encoding: a PET study. *Brain*, *120*, 123–140.
- Hazeltine, E., & Ivry, R. B. (2002). Neural structures that support implicit sequence learning. In L. Jimenez (Ed.), *Attention and implicit learning* (pp. 71–107). Amsterdam: John Benjamins.
- Hazeltine, E., Lightman, E., Schwarb, H., & Schumacher, E. H. (2011b). The boundaries of sequential modulations: evidence for set-level control. *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 1898–1914.
- Hazeltine, E., & Ruthruff, E. (2006). Modality pairing effects and the response selection bottleneck. *Psychological Research*, *70*, 504–513.
- Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: evidence for content-dependent central interference. *Cognitive Psychology*, *52*, 291–345.
- Hazeltine, E., Teague, D., & Ivry, R. B. (2002). Simultaneous dual-task performance reveals parallel response selection after practice. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(3), 527–545.
- Hazeltine, E., & Wifall, T. (2011). Searching working memory for the source of dual-task costs. *Psychological Research*, *75*, 466–475.
- Hedge, A., & Marsh, N. W. A. (1975). The effect of irrelevant spatial correspondence on two-choice response time. *Acta Psychologica*, *39*, 340–347.

- Henson, R. N., Eckstein, D., Waszak, F., Frings, C., & Horner, A. (2014). Stimulus–response bindings in priming. *Trends in Cognitive Science*, *18*, 376–384.
- Herath, P., Klingberg, T., Young, J., Amunts, K., & Roland, P. (2001). Neural correlates of dual task interference can be dissociated from those of divided attention: an fMRI study. *Cerebral Cortex*, *11*, 796–805.
- Heuer, H. (1995). Models for response–response compatibility: the effects of the relation between responses in a choice task. *Acta Psychologica*, *90*, 315–332.
- Hick, W. E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology*, *4*, 11–26.
- Holland, P. C. (1983). “Occasion–setting” in Pavlovian feature positive discriminations. In R. J. Herrnstein, & A. R. Wagner (Eds.), *Discrimination processes: Vol. 4. Quantitative analyses of behavior* (pp. 183–206). Cambridge, MA: Ballinger.
- Hommel, B. (1993). Inverting the Simon effect by intention: determinants of direction and extent effects of irrelevant spatial information. *Psychological Research*, *55*, 270–279.
- Hommel, B. (1998). Automatic stimulus–response translation in dual–task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1368–1384.
- Hommel, B. (2000). The prepared reflex: automaticity and control in stimulus–response translation (tutorial). In S. Monsell, & J. Driver (Eds.), *Attention and performance XVIII: Control of cognitive processes* (pp. 247–274). Cambridge, MA: MIT Press.
- Hommel, B. (2004). Event files: feature binding in and across perception and action. *Trends in Cognitive Science*, *8*, 494–500.
- Hommel, B. (2011). The Simon effect as tool and heuristic. *Acta Psychologica*, *136*, 189–202.
- Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC). *Behavioral and Brain Sciences*, *24*, 849–878.
- Horner, A., & Henson, R. N. (2009). Bindings between stimuli and multiple response codes dominate long–lag repetition priming in speeded classification tasks. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *35*, 757–779.
- Houk, J. C., Adams, J. L., & Barto, A. G. (1995). A model of how the basal ganglia generate and use neural signals that predict reinforcement. In J. C. Houk, J. L. Davis, & D. G. Beiser (Eds.), *Models of information processing in the basal ganglia* (pp. 249–270). Cambridge, MA: MIT Press.
- Huestegge, L., & Koch, I. (2010). Crossmodal action selection: evidence from dual–task compatibility. *Memory and Cognition*, *38*, 493–501.
- Hyman, R. (1953). Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology*, *45*, 188–196.
- Ivry, R. B., Franz, E. A., Kingstone, A., & Johnston, J. C. (1998). The psychological refractory period effect following callosotomy: uncoupling of lateralized response codes. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 463–480.
- Ivry, R. B., & Hazeltine, E. (2000). Task switching in a callosotomy patient and normal participants: evidence for response–related sources of interference. In S. Monsell, & J. Driver (Eds.), *Attention and performance* (Vol. XVIII, pp. 401–423). Cambridge, MA: MIT Press.
- Izawa, J., & Shadmehr, R. (2011). Learning from sensory and reward prediction errors during motor adaptation. *PLoS Computational Biology*, *7*, e1002012. <http://dx.doi.org/10.1371/journal.pcbi.1002012>.
- Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology*, *89*.
- Jiang, Y., & Kanwisher, N. (2003a). Common neural mechanisms for response selection and perceptual processing. *Journal of Cognitive Neuroscience*, *15*, 1095–1110.
- Jiang, Y., & Kanwisher, N. (2003b). Common neural substrates for response selection across modalities and mapping paradigms. *Journal of Cognitive Neuroscience*, *15*, 1080–1094.
- Jiang, Y., Saxe, R., & Kanwisher, N. (2004). Functional magnetic resonance imaging provides new constraints on theories of the psychological refractory period. *Psychological Science*, *15*, 390–396.

- Kamin, L. J. (1968). Attention-like processes in classical conditioning. In M. R. Jones (Ed.), *Miami symposium on the prediction of behavior: Aversive stimulation*. Miami: University of Miami Press.
- Keele, S. W. (1970). Effects of input and output modes on decision time. *Journal of Experimental Psychology*, *85*, 157–164.
- Keele, S. W., Ivry, R. B., Mayr, U., Hazeltine, E., & Heuer, H. (2003). The cognitive and neural architecture of sequence representation. *Psychological Review*, *110*, 316–339.
- Keele, S. W., Jennings, P., Jones, S., Caulton, D., & Cohen, A. (1995). On the modularity of sequence representation. *Journal of Motor Behavior*, *27*, 17–30.
- Kelso, J. A., Southard, D. L., & Goodman, D. (1979). On the coordination of two-handed movements. *Journal of Experimental Psychology: Human Perception and Performance*, *5*, 229–238.
- Keppel, G., & Underwood, B. J. (1962). Proactive inhibition in short-term retention of single items. *Journal of Verbal Learning and Verbal Behavior*, *1*, 153–161.
- Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., et al. (2010). Control and interference in task switching—a review. *Psychological Bulletin*, *136*, 849–874.
- Kiesel, A., Wendt, M., & Peters, A. (2007). Task switching: on the origin of response congruency effects. *Psychological Research*, *71*, 117–125.
- Kintsch, W. (1970). *Learning, memory, and conceptual processes*. New York: Wiley.
- Klatzky, R. L., Pellegrino, J. W., McCloskey, B. P., & Doherty, S. (1989). Can you squeeze a tomato? The role of motor representations in semantic sensibility judgments. *Journal of Memory and Language*, *28*, 56–77.
- Kleinsorge, T., & Heuer, H. (1999). Hierarchical switching in a multi-dimensional task space. *Psychological Research*, *62*, 300–312.
- Klingberg, T. (1998). Concurrent performance of two working memory tasks: potential mechanisms of interference. *Cerebral Cortex*, *8*, 593–601.
- Koch, I., & Allport, A. (2006). Cue-based preparation and stimulus-based priming of tasks in task switching. *Memory and Cognition*, *34*, 433–444.
- Koechlin, E., & Summerfield, C. (2007). An information theoretical approach to prefrontal executive function. *Trends in Cognitive Sciences*, *11*(6), 229–235. <http://dx.doi.org/10.1016/j.tics.2007.04.005>.
- Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: cognitive basis for stimulus-response compatibility—A model and taxonomy. *Psychological Review*, *97*, 253–270.
- Kornblum, S., & Lee, J.-W. (1995). Stimulus-response compatibility with relevant and irrelevant stimulus dimensions that do and do not overlap with the response. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 855–875.
- Laberge, D., Legrand, R., & Hobbie, R. K. (1969). Functional identification of perceptual and response biases in choice reaction time. *Journal of Experimental Psychology*, *79*, 295–299.
- Laberge, D., & Tweedy, J. R. (1964). Presentation probability and choice time. *Journal of Experimental Psychology*, *68*, 477–481.
- Lhermitte, F. (1983). 'Utilization behaviour' and its relation to lesions of the frontal lobes. *Brain*, *106*, 237–255.
- Liefoghe, B., Wenke, D., & De Houwer, J. (2012). Instruction-based task-rule congruency effects. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *38*, 1325–1335.
- Lien, M.-C., & Proctor, R. W. (2002). Stimulus-response compatibility and psychological refractory period effects: implications for response selection. *Psychonomic Bulletin and Review*, *9*(2), 212–238.
- Lien, M.-C., & Ruthruff, E. (2004). Task switching in a hierarchical task structure: evidence for the fragility of the task repetition benefit. *Journal of Experimental Psychology: Human Perception and Performance*, *30*, 697–713.

- Lien, M.-C., Ruthruff, E., Remington, R. W., & Johnston, J. C. (2005). On the limits of advance preparation for a task-switch: do people prepare all of the task some of the time or some of the task all the time. *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 299–315.
- Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, *95*, 492–527.
- Logan, G. D. (1990). Repetition priming and automaticity: common underlying mechanisms? *Cognitive Psychology*, *22*, 1–35.
- Logan, G. D., & Bundesen, C. (2003). Clever homunculus: Is there an endogenous act of control in the explicit task-cuing procedure? *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 575–599.
- Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review*, *108*, 393–434.
- Mayr, U., & Bryck, R. L. (2005). Sticky rules: integration between abstract rules and specific actions. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *31*, 337–350.
- Mayr, U., & Kliegl, R. (2003). Differential effects of cue changes and task changes on task-set selection costs. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*, 362–372.
- McCann, R. S., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 471–484.
- McClelland, J. L. (1979). On the time relations of mental processes: an examination of systems of processes in cascade. *Psychological Review*, *31*, 133–156.
- Mechsner, F., Kerzel, D., Knoblich, G., & Prinz, W. (2001). Perceptual basis of bimanual coordination. *Nature*, *414*, 69–73.
- Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory phenomena. *Psychological Review*, *104*, 749–791.
- Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of human multiple task performance: the EPIC information-processing architecture and strategic response deferment model. *Psychological Review*, *104*, 1–65.
- Meyer, D. E., & Schvaneveldt, R. W. (1971). Facilitation in recognizing pairs of words: evidence of a dependence between retrieval operations. *Journal of Experimental Psychology*, *90*, 227–234.
- Miller, J. (1982). Discrete versus continuous models of human information processing: in search of partial output. *Journal of Experimental Psychology: Human Perception and Performance*, *8*, 273–296.
- Miller, J. (1985). A hand advantage in preparation of simple keypress responses: reply to Reeve and Proctor (1984). *Journal of Experimental Psychology: Human Perception and Performance*, *11*, 221–233.
- Miller, J. (1988). Discrete and continuous models of human information processing: theoretical distinctions and empirical results. *Acta Psychologica*, *67*, 191–257.
- Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*, 167–202.
- Miller, E. K., Nieder, A., Freedman, D. J., & Wallis, J. D. (2003). Neural correlates of categories and concepts. *Current Opinion in Neurobiology*, *13*, 198–203.
- Milner, B. (1963). Effects of different brain lesions on card sorting. *Archives of Neurology*, *9*, 90–100.
- Monsell, S., & Driver, J. (2000). Banishing the control homunculus. In S. Monsell, & J. Driver (Eds.), *Attention and performance XVIII: Control of cognitive processes* (pp. 3–32). Cambridge, Massachusetts: MIT Press.

- Mordkoff, J. T., & Hazeltine, E. (2011). Parallel patterns of spatial compatibility and spatial congruence...as long as you don't look too closely. *Acta Psychologica*, *136*, 253–258.
- Müsseler, J., & Hommel, B. (1997). Blindness to response-compatible stimuli. *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 861–872.
- Nagel, I. E., Schumacher, E. H., Goebel, R., & D'Esposito, M. (2008). Functional MRI investigation of verbal selection mechanisms in lateral prefrontal cortex. *NeuroImage*, *43*, 801–807.
- Navon, D., & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, *13*, 435–448.
- Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: evidence from performance measures. *Cognitive Psychology*, *19*, 1–32.
- Norman, D. A., & Shallice, T. (1986). Attention to action: willed and automatic control of behavior. In J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation* (Vol. 4, pp. 1–18). New York: Plenum.
- Notebaert, W., & Verguts, T. (2008). Cognitive control acts locally. *Cognition*, *106*, 1071–1080.
- O'Reilly, R. C. (2010). The what and how of prefrontal cortical organization. *Trends in Neurosciences*, *33*, 355–361.
- Pashler, H. (1984). Processing stages in overlapping tasks: evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 358–377.
- Pashler, H. (1989). Dissociations and dependencies between speed and accuracy: evidence for a two-component theory of divided attention in simple tasks. *Cognitive Psychology*, *21*, 469–514.
- Pashler, H. (1990). Do response modality effects support multiprocessor models of divided attention. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(4), 826–842.
- Pashler, H. (1994a). Dual-task interference in simple tasks: data and theory. *Psychological Bulletin*, *116*, 220–244.
- Pashler, H. (1994b). Graded capacity-sharing in dual-task interference? *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 330–342.
- Pashler, H., & Baylis, G. (1991). Procedural learning: 1. Locus of practice effects in speeded choice tasks. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *17*(1), 20–32.
- Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology*, *41A*, 19–45.
- Pinel, J. P. J., & Treit, D. (1979). Conditioned defensive burying in rats: availability of burying materials. *Animal Learning and Behavior*, *7*, 392–396.
- Pollack, I. (1959). Message uncertainty and message reception. *The Journal of the Acoustical Society of America*, *31*, 1500–1508.
- Prinz, W. (1990). A common coding approach to perception and action. In O. Neumann, & W. Prinz (Eds.), *Relationships between perception and action* (pp. 167–201). Berlin: Springer-Verlag.
- Proffitt, D. R. (2006). Distance perception. *Current Directions in Psychological Science*, *15*, 131–135.
- Rabbitt, P. M. A. (1959). Effects of independent variations in stimulus and response probability. *Nature*, *183*, 1212.
- Rabbitt, P. M. A., & Vyas, S. M. (1973). What is repeated in the “repetition effect”? In S. Kornblum (Ed.), *Attention and performance* (Vol. IV, pp. 327–342). London: Academic Press.
- Rauch, S. L., Savage, C. R., Brown, H. D., Curran, T., Alpert, N. M., Kendrick, A., & Kosslyn, S. M. (1995). A PET investigation of implicit and explicit sequence learning. *Human Brain Mapping*, *3*, 271–286.

- Reeve, T. G., & Proctor, R. W. (1984). On the advance preparation of discrete finger responses. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 541–553.
- Reeve, T. G., & Proctor, R. W. (1985). Non-motoric translation processes in the preparation of discrete finger responses: a rebuttal of Miller's (1985) analysis. *Journal of Experimental Psychology: Human Perception and Performance*, *11*, 234–240.
- Reeve, T. G., & Proctor, R. W. (1990). The salient-features coding principle for spatial- and symbolic compatibility effects. In R. W. Proctor, & T. G. Reeve (Eds.), *Stimulus-response compatibility* (pp. 163–180). Amsterdam: North-Holland.
- Reisberg, D., Baron, J., & Kemler, D. G. (1980). Overcoming Stroop interference: the effects of practice on distractor potency. *Journal of Experimental Psychology: Human Perception and Performance*, *6*, 140–150.
- Rescorla, R. A. (1972). Second-order conditioning: implications for theories of learning. In F. J. McGuigan, & D. Lumsden (Eds.), *Contemporary approaches to conditioning and learning*. New York: Winston.
- Rescorla, R. A. (1988a). Behavioral studies of Pavlovian conditioning. *Annual Review of Neuroscience*, *11*, 329–352.
- Rescorla, R. A. (1988b). Pavlovian conditioning: it's not what you think it is. *American Psychologist*, *43*, 151–160.
- Rescorla, R. A., & Wagner, A. R. (1972). A theory of Pavlovian conditioning: variations in the effectiveness of reinforcement and nonreinforcement. In *Classical conditioning II: Current research and theory* (pp. 64–99). New York: Appleton-Century-Crofts.
- Rigotti, M., Barak, O., Warden, M. R., Wang, X.-J., Daw, N. D., Miller, E. K., et al. (2013). The importance of mixed selectivity in complex cognitive tasks. *Nature*, *497*, 585–590.
- Rogers, R., & Monsell, S. (1995). The costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *124*, 207–231.
- Rosenbaum, D. A. (1980). Human movement initiation: specification of arm, direction, and extent. *Journal of Experimental Psychology: General*, *109*, 444–474.
- Rosenbaum, D. A. (1983). The movement precuing technique: assumptions, applications, and extensions. In R. A. Magill (Ed.), *Memory and control of action* (pp. 230–274). Amsterdam: North-Holland Publishing Company.
- Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J., & Jorgensen, M. (1990). Constraints for action selection: overhand versus underhand grips. In M. Jeannerod (Ed.), *Attention and performance XIII: Motor representation and control* (pp. 321–342). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Rugg, M. D., Allan, K., & Birch, C. S. (2000). Electrophysiological evidence for the modulation of retrieval orientation by depth of study processing. *Journal of Cognitive Neuroscience*, *12*(4), 664–678. <http://dx.doi.org/10.1162/089892900562291>.
- Rugg, M. D., & Wilding, E. L. (2000). Retrieval processing and episodic memory. *Trends in Cognitive Sciences*, *4*(3), 108–115. [http://dx.doi.org/10.1016/s1364-6613\(00\)01445-5](http://dx.doi.org/10.1016/s1364-6613(00)01445-5).
- Ruthruff, E., Johnston, J. C., & Van Selst, M. (2001). Why practice reduces dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 3–21.
- Ruthruff, E., Johnston, J. C., Van Selst, M., Whitsell, S., & Remington, R. W. (2003). Vanishing dual-task interference after practice: Has the bottleneck been eliminated or is it merely latent? *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 280–289.
- Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science*, *274*, 1926–1928.
- Sakai, K. (2008). Task set and prefrontal cortex. *Annual Review of Neuroscience*, *31*, 219–245. Palo Alto: Annual Reviews.
- Salvucci, D. D., & Taatgen, N. A. (2010). *The multitasking mind*. New York: Oxford University Press.

- Schmidt, J. R., & Weissman, D. H. (2014). Congruency sequence effects without feature integration or contingency learning confounds. *PLoS One*, *9*.
- Schneider, W. (1985). Toward a model of attention and the development of automatic processing. In M. I. Posner, & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 475–492). Hillsdale, NJ: Erlbaum.
- Schneider, D. W. (2014). Isolating a mediated route for response congruency effects in task switching. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *41*, 235–245.
- Schneider, D. W., & Anderson, J. R. (2011). A memory-based mode of Hick's law. *Cognitive Psychology*, *62*, 193–222.
- Schneider, D. W., & Logan, G. D. (2007). Retrieving information from a hierarchical plan. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *33*, 1076–1091.
- Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review*, *84*, 1–66.
- Schultz, W., Romo, R., Ljungberg, T., Mirenowicz, J., Hollerman, J. R., & Dickinson, A. (1995). Reward-related signals carried by dopamine neurons. In J. C. Houk, J. L. Davis, & D. G. Beiser (Eds.), *Models of information processing in the basal ganglia* (pp. 233–248). Cambridge, MA: MIT Press.
- Schumacher, E. H., & D'Esposito, M. (2002). Neural implementation of response selection in humans as revealed by localized effects of stimulus-response compatibility on brain activation. *Human Brain Mapping*, *17*, 193–201.
- Schumacher, E. H., Elston, P. A., & D'Esposito, M. (2003). Neural evidence for representation-specific response selection. *Journal of Cognitive Neuroscience*, *15*, 1111–1121.
- Schumacher, E. H., & Schwarb, H. (2009). Parallel response selection disrupts sequence learning under dual-task conditions. *Journal of Experimental Psychology: General*, *138*, 270–290.
- Schumacher, E. H., Schwarb, H., Lightman, E., & Hazeltine, E. (2011). Investigating the modality specificity of response selection using a temporal flanker task. *Psychological Research*, *75*, 499–512.
- Schumacher, E. H., Seymour, T. L., Glass, J. M., Kieras, D. E., & Meyer, D. E. (2001). Virtually perfect time sharing in dual-task performance: uncorking the central attentional bottleneck. *Psychological Science*, *12*, 101–108.
- Schwarb, H., & Schumacher, E. H. (2009). Neural evidence of a role for spatial response selection in the learning of spatial sequences. *Brain Research*, *1247*, 114–125.
- Schwarb, H., & Schumacher, E. H. (2010). Implicit sequence learning is represented by stimulus-response rules. *Memory and Cognition*, *38*, 677–688.
- Schwarb, H., & Schumacher, E. H. (2012). Generalized lessons about sequence learning from the study of the serial reaction time task. *Advances in Cognitive Psychology*, *8*, 165–178.
- Seidler, R. D., Purushotham, A., Kim, S.-G., Ugurbil, K., Willingham, D. B., & Ashe, J. (2002). Cerebellum activation associated with performance change but not motor learning. *Science*, *296*, 2043–2046.
- Shaffer, L. H. (1965). Choice reaction with variable S-R mapping. *Journal of Experimental Psychology*, *70*, 284–288.
- Shallice, T. (1982). Specific impairments of planning. *Philosophical Transactions of the Royal Society of London B*, *298*, 199–209.
- Siegel, M., Buschman, T. J., & Miller, E. K. (2015). Cortical information flow during flexible sensorimotor decisions. *Science*, *384*, 1352–1355.
- Simon, J. R. (1969). Reactions towards the source of stimulation. *Journal of Experimental Psychology*, *81*, 174–176.
- Simon, J. R., & Rudell, A. P. (1967). Auditory S-R compatibility: the effect of an irrelevant cue on information processing. *Journal of Applied Psychology*, *51*, 300–304.
- Smith, M. C. (1967). Theories of the psychological refractory period. *Psychological Bulletin*, *67*, 202–213.

- Soto, F. A., & Wasserman, E. A. (2012). A category-overshadowing effect in pigeons: support for the common elements model of object categorization learning. *Journal of Experimental Psychology: Animal Behavior Processes*, *38*, 322–328.
- Spapé, M. M., & Hommel, B. (2008). He said, she said: episodic retrieval induces conflict adaptation in an auditory Stroop task. *Psychonomic Bulletin and Review*, *15*, 1117–1121.
- Spivey, M. J., Dale, R., Knoblich, G., & Grosjean, M. (2010). Do curved reaching movements emerge from competing perceptions? *Journal of Experimental Psychology: Human Perception and Performance*, *36*, 251–254.
- Stelzel, C., Schumacher, E. H., Schubert, T., & D'Esposito, M. (2006). The neural effect of stimulus-response modality compatibility on dual-task performance: an fMRI study. *Psychological Research*, *70*, 514–525.
- Sternberg, S. (1969). The discovery of processing stages: extension of Donder's method. In W. G. Koster (Ed.), *Attention and performance* (Vol. II, pp. 276–315). Amsterdam: North Holland.
- Stoffels, E. J. (1996). Uncertainty and processing routes in the selection of a response. An S-R compatibility study. *Acta Psychologica*, *94*, 227–252.
- Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662.
- Stuss, D. T., & Benson, D. F. (1984). Neuropsychological studies of the frontal lobes. *Psychological Bulletin*, *95*, 3–28.
- Swinnen, S. (2002). Intermanual coordination: from behavioural principles to neural-network interactions. *Nature Reviews Neuroscience*, *3*, 350–361.
- Szameitat, A. J., Schubert, T., Müller, K., & von Cramon, D. Y. (2002). Localization of executive function in dual-task performance with fMRI. *Journal of Cognitive Neuroscience*, *14*, 1184–1199.
- Taylor, J. A., & Ivry, R. B. (2013). Context-dependent generalization. *Frontiers in Human Neuroscience*, *7*(171). <http://dx.doi.org/10.3389/fnhum.2013.00171>.
- Theios, J. (1975). The components of response latency in simple human information processing tasks. In P. M. A. Rabbitt, & S. Dornic (Eds.), *Attention and performance* (Vol. V, pp. 418–440). London: Academic Press.
- Thompson, R. F. (1990). Neural mechanisms of classical conditioning in mammals. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *329*, 161–170.
- Toni, I., Krams, M., Turner, R., & Passingham, R. E. (1998). The time course of changes during motor sequence learning: a whole-brain fMRI study. *NeuroImage*, *8*, 50–61.
- Tulving, E. (1983). *Elements of episodic memory*. New York: Oxford University Press.
- Ullsperger, M., Bylsma, L. M., & Botvinick, M. M. (2005). The conflict adaptation effect: it's not just priming. *Cognitive, Affective and Behavioral Neuroscience*, *5*, 467–472.
- Usher, M., & McClelland, J. L. (2001). The time course of perceptual choice: the leaky, competing accumulator model. *Psychological Review*, *108*, 550–592.
- Verbruggen, F., McLaren, I. P. L., & Chambers, C. D. (2014). Banishing the control homunculi in studies of action control and behavior change. *Perspectives in Psychological Science*, *9*, 497–524.
- Verguts, T., & Notebaert, W. (2008). Hebbian learning and cognitive control: dealing with specific and non-specific adaptation. *Psychological Review*, *115*, 518–525.
- Wallace, R. J. (1971). S-R compatibility and the idea of a response code. *Journal of Experimental Psychology*, *88*, 354–360.
- Wallis, J. D., Anderson, K. C., & Miller, E. K. (2001). Single neurons in the prefrontal cortex encode abstract rules. *Nature*, *411*, 953–956.
- Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long-term priming: role of episodic stimulus-task bindings in task-shift costs. *Cognitive Psychology*, *46*, 361–413.
- Watkins, O. C., & Watkins, M. J. (1975). Buildup of proactive inhibition as a cue-overload effect. *Journal of Experimental Psychology: Human Learning and Memory*, *104*, 442–452.

- Welford, A. T. (1952). The “psychological refractory period” and the timing of high-speed performance—a review and a theory. *British Journal of Psychology*, *43*(4), 2–19.
- Welford, A. T. (1958). *Ageing and human skill*. London: Oxford University Press.
- Welford, A. T. (1967). Single channel operation in the brain. *Acta Psychologica*, *27*, 5–22.
- Wenke, D., Gaschler, R., & Nattkemper, D. (2007). Instruction-induced feature binding. *Psychological Research*, *71*, 92–106.
- Wickens, D. D. (1970). Encoding categories of words: an empirical approach to meaning. *Psychological Review*, *77*, 1–15.
- Wickens, D. D. (1972). Characteristics of word encoding. In A. W. Melton, & E. Martin (Eds.), *Coding processes in human memory* (pp. 191–215). Washington, D.C.: Winston/Wiley.
- Wickens, D. D., Born, D. G., & Allen, C. K. (1963). Proactive inhibition and item similarity in short-term memory. *Journal of Verbal Learning and Verbal Behavior*, *2*(5–6), 440–445.
- Wifall, T., Hazeltine, E., & Mordkoff, J. T. (2015). The roles of stimulus and response uncertainty in forced-choice performance: an amendment of Hick/Hyman Law. *Psychological Research*. <http://dx.doi.org/10.1007/s00426-015-0675-8>.
- Wifall, T., McMurray, B., & Hazeltine, E. (2014). Perceptual similarity affects the learning curve (but not necessarily learning). *Journal of Experimental Psychology: General*, *143*, 312–331.
- Wilding, E. L. (1999). Separating retrieval strategies from retrieval success: an event-related potential study of source memory. *Neuropsychologia*, *37*(4), 441–454. [http://dx.doi.org/10.1016/S0028-3932\(98\)00100-6](http://dx.doi.org/10.1016/S0028-3932(98)00100-6).
- Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review*, *105*, 558–584.
- Willingham, D. B., Nissen, M. J., & Bullemer, P. (1989). On the development of procedural knowledge. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *15*, 1047–1060.
- Willingham, D. B., Wells, L. A., Farrell, J. M., & Stemwedel, M. E. (2000). Implicit motor sequence learning is represented in response locations. *Memory and Cognition*, *28*, 366–375.
- Wright, C. E. (1990). Generalized motor programs: reevaluating claims of effector independence. In M. Jeannerod (Ed.), *Attention and performance* (Vol. XIII, pp. 294–320). Hillsdale, NJ: Lawrence Erlbaum.
- Zacks, J. M., & Swallow, K. M. (2007). Event segmentation. *Current Directions in Psychological Science*, *16*, 80–84.
- Ziessler, M., & Nattkemper, D. (2001). Learning of event sequences is based on response effect learning: further evidence from serial reaction task. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *27*, 595–613.
- Ziessler, M., & Nattkemper, D. (2002). Effect anticipation in action planning. In W. Prinz, & B. Hommel (Eds.), *Attention and performance* (Vol. XIX, pp. 645–672). Oxford: University Press.