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Hierarchical Task Representation: Task Files and Response Selection

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Abstract
Human behavior is remarkably complex—even during the performance of relatively simple tasks—yet it is often assumed that learned associations between stimuli and responses provide the representational substrate for action selection. Here, we introduce an alternative framework, called a *task file*, that includes hierarchical associations between stimulus features, response features, goals, and drives, which may overcome the limitations inherent in the conceptualization of response selection as being based solely on associations between stimuli and responses. We then review evidence from our own experimental research showing that even in the context of performing relatively easy tasks, the stimulus-response-association approach to response selection is inadequate to account for the interactions between discrete responses. Instead, response selection may emerge from competition between linked representations at multiple levels.

Keywords
action, cognitive control, goal-directed behavior, perceptual-motor processing, task structure

How do we achieve flexible goal-directed behavior when we are continually confronted with an array of stimuli and a variety of potential responses to those stimuli? This fundamental operation is the purview of response selection, the set of cognitive processes that choose (activate) a behavior (response) to a stimulus given one's goals and current situation. Many theories of response selection implicitly or explicitly assume a simple associative mechanism linking stimuli to responses. Botvinick, Braver, Barch, Carter, and Cohen's (2001) *conflict-monitoring model* is a good example of this. In it, the environment activates stimulus representations, which in turn activate responses associated with those stimuli. Separate conflict-monitoring and control processes bias which stimulus-response association produces an action. This mechanism has been highly productive. In fact, it is difficult to imagine a framework for response selection that does not involve, at some level, stimulus-response associations.

However, there is a large body of data that are not readily accommodated by the view that response selection is simply the activation of the most appropriate independent stimulus-response association by environmental and control processes. We surveyed these findings in Hazeltine and Schumacher (2016), where we concluded that conceptualizing response selection as the activation of particular stimulus-response associations fails to capture critical features of behavior relating to the ability to encode abstract relationships across sets of stimuli and responses (see also Rescorla, 1988). An alternative approach, outlined here, is to apply principles from accounts of frontal-lobe function in which hierarchical systems organize behaviors to meet current task goals (e.g., Botvinick, 2008; Koechlin, 2008). Much of this theoretical work has focused on how discrete responses are flexibly selected so that action is driven by context, goals, and plans rather than strictly by the current environment.

Here, we argue that such mechanisms should not be ignored when considering discrete choice reaction tasks with fixed mappings and minimal planning requirements. Rather, we propose that prefrontal mechanisms described

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by existing theories actually play an integral role in the formation of what we call *task files*, which represent information spanning both perceptual features and abstract goals. Because these task files compete across a range of representational levels, response selection does not necessarily rely on control processes to select the most appropriate stimulus-response association based on independent representations of intentions. Instead, the most active action is the one that best satisfies the constraints provided by the environment and the organism's motivational state. Moreover, associative learning can take place across these various levels, such that practice tunes the links between sensory, motoric, and intentional information rather than strengthening individual stimulus-response associations. In short, we emphasize that there are no meaningful distinctions between stimulus and motor representations and the control processes that mediate them.

The framework outlined here is not a rigorous theory of response selection; rather, it represents an approach for combining insights from theories of functional organization of prefrontal cortex and behavioral studies emphasizing the complexity of action representation. After describing the framework, we review some behavioral findings from our laboratories to illustrate how it may be useful.

Task-File Representation

The framework for representing tasks (shown in Figure 1) takes stimulus features as input and forms increasingly abstract representations to identify potential actions, eventually encoding more complex aspects of tasks and behavior. This hierarchical approach is inspired by a range of neurophysiological findings and computational models of prefrontal cortex (e.g., Badre, 2008; Koechlin, 2008; Miller & Cohen, 2001; Norman & Shallice, 1986). These abstract properties at the higher levels of the hierarchy are diverse and multifaceted. For example, representations based on spatial properties might include transformations to different reference frames (e.g., moving from retinotopic coordinates to head- or shoulder-centered coordinates; Andersen, Snyder, Bradley, & Xing, 1997), and representations of an object's properties might activate units coding potential ways to interact with the object (e.g., Cavina-Pratesi et al., 2006). Because these representations include more information relating to possible means of interacting with stimuli, they lead to the increasing activation of specific responses.

Described in this way, the proposed flow of information might seem only trivially different from that described by a standard stimulus-response-association account (e.g., Anderson et al., 2004; Kornblum, Hasbroucq, & Osman, 1990) in that it depicts sensory input activating responses in a feedforward fashion. However, we highlight two critical differences. First, the path from stimulus features to response units is mediated by abstract action representations whose contents are biased by input from more anterior portions of the network. Viewing a steering wheel, for example, does not directly activate particular movements of the hands and arms but rather activates the abstract concept of turning the wheel to steer. These abstract representations serve to modulate processing rather than leading directly to overt responses.

The second major difference is that the flow of information is bidirectional, and input to the motor units primarily comes from anterior regions, which link the abstract action representations with goals. In essence, we assume that anterior regions bias the dominant transformation or action in posterior regions (cf. Miller & Cohen, 2001). As we move up the hierarchy, the action representations become increasingly complex and integrative, linking related actions into groups that more or less define tasks and linking these possible tasks with motivational factors. Thus, the appropriate actions are activated in a goal-directed fashion. This conceptualization is similar to recent theories' characterizations of functional hierarchies within prefrontal cortex (see Badre, 2008), but we make no distinction between individual stimulus-response associations and the control processes that activate them. Moreover, associative learning is assumed to constantly take place between various levels of the networks, but little of this learning would clearly fit the description of a stimulus-response association. The changes in connections take place across diverse coactivated representations to tune goal-directed behavior.

We refer to the linked activation across the network as a task file (see Figure 1). This term is derived from Hommel's *event file* (Hommel, 1998), which itself was inspired by Kahneman's *object file* (Kahneman, Treisman, & Gibbs, 1992). In this context, the task file framework extends previous work that has considered how distinct features are integrated into meaningful representational units. In comparison to event files, task files include diverse components that not only bind stimulus and response features but also bind sets of responses to each other and to intentional factors. Abstract rules are not applied to stimuli to compute a response (and form an event file) but are encoded as part of the task file, so stimuli, responses, rules, contexts, and intentional states form mutually excitatory assemblages. Such an approach reduces the need for homuncular control systems, because task files with strong activation based on affordances driven by posterior regions can compete directly with task files with strong activation based on task valuation from anterior regions. Attention, memory, error monitoring, and other motivational and control processes may be engaged through this competition.

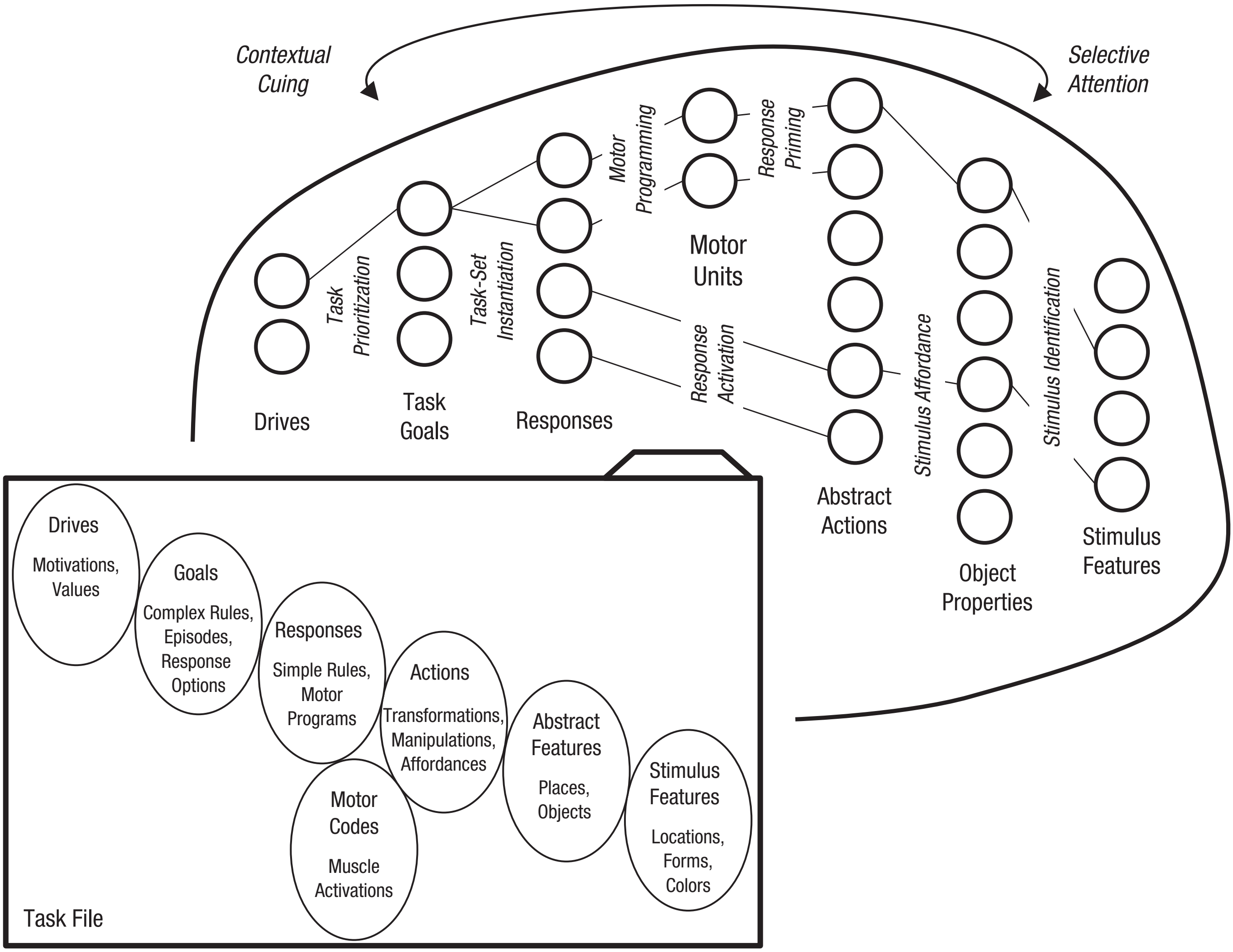

Fig. 1. An illustration of continuous perceptual-motor processes schematized into separate representational domains, depicted as labeled columns of nodes. The functions served by communication between domains are indicated in italics. Links between all nodes are bidirectional. The inset shows the contents of the resulting task file when the relevant subset of nodes (given a current situation) are active and all the domains are linked. Larger text depicts the categories of information included in the file, and smaller text describes examples. We assume that some actions may be produced without strongly activating information in each domain.

The task-file account does not postulate a single generic mechanism for selecting responses but instead relies on a distributed set of processes that are contingent on the particular composition of the task. Indeed, with neuroimaging studies, we have shown that distinct brain regions are engaged by response selection depending on the modality of the stimulus or response (e.g., Cookson, Hazeltine, & Schumacher, 2016; Nagel, Schumacher, Goebel, & D'Esposito, 2008; Schumacher, Elston, & D'Esposito, 2003; Schumacher, Schwarb, Lightman, & Hazeltine, 2011; Stelzel, Schumacher, Schubert, & D'Esposito, 2006). These results are consistent with the proposal that response selection is mediated by different brain regions depending on the type of stimulus and response.

Task Files Account for Interactions Between Discrete Responses

Most of the evidence for the abstract coding of tasks in our own research has come from experiments examining the interactions between discrete responses performed close together in time. In one study, Hazeltine (2005) showed that simultaneously performed left- and right-hand responses could be congruent or incongruent with each other depending on how participants encoded the tasks. For example, if participants thought of their responses as distance from the body's midline, then responses with corresponding fingers (e.g., the two ring fingers) were congruent. However, if participants thought of their responses as movements along a left-right axis, then responses in the same left-right order (e.g., left ring finger and right middle finger—thumbs were excluded) were congruent. Even though the stimuli were held constant across conditions, the patterns of congruency changed depending on whether participants thought of the tasks as involving movements toward or away from the body or toward the left or the right, indicating that cross talk between responses can occur at an abstract level of representation driven by the conceptualization of the task (cf. Duncan, 1978).

Studies of dual-task interference have also investigated the interactions between responses produced in close temporal proximity. Across a wide variety of conditions, dual-task experiments have shown that performance on one or both tasks suffers the closer together in time the two tasks' stimuli appear. This nearly ubiquitous dual-task cost has led many researchers to propose a generic bottleneck at response selection (see Pashler, 1994). However, there is now considerable evidence that dual-task costs do not simply reflect the limitation that only a single stimulus-response association can be activated at a time. Rather, under some conditions, dual-task interference essentially disappears with practice (e.g., Hazeltine, Teague, & Ivry, 2002; Schumacher, Seymour, Glass, Kieras, & Meyer, 2001). Moreover, Hazeltine, Ruthruff, and Remington (2006) observed that when a visual-manual and an auditory-vocal task were practiced together, dual-task costs became very small, but when the pairings were swapped to form a visual-vocal and an auditory-manual task, the costs remained robust throughout practice. If response selection emerges simply from an association of any response with any stimulus, it is not clear why some stimulus-response pairs would interfere with each other more than others. Therefore, we propose that dual-task delays are not caused by generic interference resulting from competition between stimulus-response associations. Instead, they are caused by the difficulty people have delimitating and segregating the representations of multiple competing tasks (see Halvorson & Hazeltine, 2015). Furthermore, some stimulus-response modality pairings allow for easier segregation than others. This suggests that it is the relationship between the stimulus-response associations (encoded in the task file) that determines interference.

Discrete responses can interact even when task operations do not overlap in time, and these interactions depend on more than stimulus-response features (see Dreisbach, 2012; Mayr & Bryck, 2005). For example, when responses that are signaled by either congruent or incongruent stimuli are separated by a brief interval, the congruency of the previous trial can affect the size of the congruency effect on a current trial. This congruency sequence effect may indicate the persistence of control processes from one trial to the next (Botvinick et al., 2001; Gratton, Coles, & Donchin, 1992). To examine what must be shared across trials for the congruency sequence effect to be observed, our laboratories collaborated on a set of experiments using a temporal flanker task in which stimuli could be presented either visually or aurally (Hazeltine, Lightman, Schwarb, & Schumacher, 2011). We found that the congruency sequence effect was not determined by whether successive trials shared the same stimulus modality. Rather, it was the pairing of modality and task that determined whether a congruency sequence effect was observed. That is, if participants could use modality to segregate stimulus-response pairs into distinct tasks (viz., a visual task and an auditory task), then congruency sequence effects did not span modalities; however, if stimulus modality was independent of task, then congruency sequence effects spanned modalities. Thus, it is the task structure that determines the boundaries of control from one trial to the next, which is consistent with the proposal that task files flexibly organize separate stimuli and responses into behaviorally meaningful groups (see also Akçay & Hazeltine, 2008).

Discrete responses also interact when associations between them are learned, as in the serial-reaction-time procedure (Nissen & Bullemer, 1987). In this procedure, participants perform a choice reaction task whose trial order has an underlying structure. There is substantial evidence suggesting that participants are learning more than simple associations between stimulus-response pairs in this procedure (see Schwarb & Schumacher, 2010). Hazeltine (2002) showed that consequences of responses affected the transfer of learning when new motor responses were required, suggesting that action goals are incorporated into the sequence representation. Schumacher and Schwarb (2009) showed in a dual-task procedure that the learning of a sequence in one task increased when the interval between the two tasks increased. This suggests that more temporal segregation between the stimuli improved participants' ability to represent the separate tasks. Similarly, Halvorson, Wagschal, and Hazeltine (2013) showed that conceptual knowledge provided to participants to help them organize the tasks affected how sequences were learned. These results are consistent with the idea that hierarchical information is encoded into task files and used to guide learning processes (see also Freedberg, Wagschal, & Hazeltine, 2014).

Conclusion

We have briefly sketched how theoretical developments in the understanding of prefrontal cortex can be applied to the richness of behavior observed in simple laboratory procedures. The primary insight is that the task, rather than the stimulus-response association, is the primary representation guiding action. The task file conceptualizes tasks as collections of related stimuli, responses, contexts, goals, and motivations. In this way, it is more than a memory schema (Norman & Shallice, 1986), which essentially is an abstract affordance representation dissociated from the goals and intentions of the organism. Because of this, Norman and Shallice's model requires an external control process (e.g., the supervisory attentional system) to resolve conflict within the information-processing system. The rich representation included in the task file may allow us to overcome conflict in the system through inherent competitive processes (e.g., predictive coding, Friston, 2009; mutual inhibition) within and between task files. We propose that considering response selection within this framework may increase our understanding of how humans organize information processing to achieve our goals—especially in complex real-world situations.

Recommended Reading

Badre, D., & D'Esposito, M. (2009). Is the rostro-caudal axis of the frontal lobe hierarchical? *Nature Reviews Neuroscience*, *10*, 659–669. A review of neuroscientific theories for an anterior-posterior processing gradient in prefrontal cortex.

Hazeltine, E., & Schumacher, E. H. (2016). (See References). A more thorough review of the limitations of the stimulus-response association approach to response selection.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC). *Behavioral & Brain Sciences*, *24*, 849–878. A more complete theory for how stimulus and response features are integrated to guide behavior.

Norman, D. A., & Shallice, T. (1986). (See References). An influential article describing how control processes may work within and through task representations.

Rescorla, R. A. (1988). (See References). A review from behavioral psychology describing the limits of the ability of stimulus-response association mechanisms to explain animal learning.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

References

Akçay, Ç., & Hazeltine, E. (2008). Conflict adaptation depends on task structure. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 958–973.

Andersen, R. A., Snyder, L. H., Bradley, D. C., & Xing, J. (1997). Multimodal representations of space in the posterior parietal cortex and its use in planning movements. *Annual Review of Neuroscience*, *20*, 303–330.

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.

Badre, D. (2008). Cognitive control, hierarchy, and the rostrocaudal organization of the frontal lobes. *Trends in Cognitive Sciences*, *12*, 193–200.

Botvinick, M. M. (2008). Hierarchical models of behavior and prefrontal function. *Trends in Cognitive Sciences*, *12*, 201–208.

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.

Cavina-Pratesi, C., Valyear, K. F., Culham, J. C., Köhler, S., Obhi, S. S., Marzi, C. A., & Goodale, M. A. (2006). Dissociating arbitrary stimulus-response mapping from movement planning during preparatory period: Evidence from event-related functional magnetic resonance imaging. *Journal of Neuroscience*, *26*, 2704–2713.

Cookson, S. L., Hazeltine, E., & Schumacher, E. H. (2016). Neural representations of stimulus-response associations during task preparation. *Brain Research*, *1648*, 496–505.

Dreisbach, G. (2012). Mechanisms of cognitive control: The functional role of task rules. *Current Directions in Psychological Science*, *21*, 227–231.

Duncan, J. (1978). Response selection in spatial choice reaction: Further evidence against associative models. *The Quarterly Journal of Experimental Psychology*, *30*, 429–440.

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.

Friston, K. (2009). The free-energy principle: A rough guide to the brain? *Trends in Cognitive Sciences*, *13*, 293–301.

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.

Halvorson, K. M., & Hazeltine, E. (2015). Do small dual-task costs reflect ideomotor compatibility or the absence of crosstalk? *Psychonomic Bulletin & Review*, *22*, 1403–1409.

Halvorson, K. M., Wagschal, T. T., & Hazeltine, E. (2013). Conceptualization of task boundaries preserves implicit sequence learning under dual-task conditions. *Psychonomic Bulletin & Review*, *20*, 1005–1010.

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, England: Oxford University Press.

Hazeltine, E. (2005). Response-response compatibility during bimanual movements: Evidence for the conceptual coding of action. *Psychonomic Bulletin & Review*, *12*, 682–688.

Hazeltine, E., Lightman, E., Schwarb, H., & Schumacher, E. H. (2011). 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., & 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., & Schumacher, E. H. (2016). Understanding central processes: The case against simple stimulus-response associations and for complex task representation. In

B. Ross (Ed.), *Psychology of learning and motivation* (Vol. 64, pp. 195–245). Cambridge, MA: Elsevier.

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*, 527–545.

Hommel, B. (1998). Event files: Evidence for automatic integration of stimulus–response episodes. *Visual Cognition*, *5*, 183–216.

Kahneman, D., Treisman, A. M., & Gibbs, B. J. (1992). The reviewing of object files: Object specific integration of information. *Cognitive Psychology*, *24*, 175–219.

Koechlin, E. (2008). The cognitive architecture of the human lateral prefrontal cortex. In P. Haggard, Y. Rosetti, & M. Kawato (Eds.), *Attention and performance* (Vol. XXII, pp. 483–510). New York, NY: Oxford University Press.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility—A model and taxonomy. *Psychological Review*, *97*, 253–270.

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.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*, 167–202.

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.

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, NY: Plenum Press.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116*, 220–244.

Rescorla, R. A. (1988). Pavlovian conditioning: It's not what you think it is. *American Psychologist*, *43*, 151–160.

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. (2010). Implicit sequence learning is represented by stimulus-response rules. *Memory & Cognition*, *38*, 677–688.

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.