# Grounding Cognitive Control in Associative Learning

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Cognitive control covers a broad range of cognitive functions, but its research and theories typically remain tied to a single domain. Here we outline and review an associative learning perspective on cognitive control in which control emerges from associative networks containing perceptual, motor, and goal representations. Our review identifies 3 trending research themes that are shared between the domains of *conflict adaptation*, *task switching*, *response inhibition*, and *attentional control*: Cognitive control is context-specific, can operate in the absence of awareness, and is modulated by reward. As these research themes can be envisaged as key characteristics of learning, we propose that their joint emergence across domains is not coincidental but rather reflects a (latent) growth of interest in learning-based control. Associative learning has the potential for providing broad-scaled integration to cognitive control theory, and offers a promising avenue for understanding cognitive control as a self-regulating system without postulating an ill-defined set of homunculi. We discuss novel predictions, theoretical implications, and immediate challenges that accompany an associative learning perspective on cognitive control.

*Keywords:* attentional control, cognitive control, conflict adaptation, response inhibition, task switching

Why do we do the things we do? Over a century ago, Thorndike (1911, 1933) argued that all behavior derives from learned stimulus–response (S-R) associations that are driven by reinforcement. Tolman (1925, 1948), in strong contrast, defended the idea that behavior must be intrinsically goal-directed. For a long time, this dichotomy inspired much debate in cognitive psychology. By now, however, it is generally accepted that both mechanisms contribute to behavior. They are extensively studied in literatures on (habit) learning and cognitive control, respectively, with the latter being an umbrella term for processes that allow for the maintenance of goal-directed behavior in the face of challenging, ambiguous situations (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Miller & Cohen, 2001). In fact, learning and cognitive control are often considered to be complementary functions: Whereas learning is concerned with acquiring new (or updating old) knowledge and skills, cognitive control enables us to counter negative effects of such learning (i.e., when it opposes current

goals). For example, we have learned to pick up the phone when it rings. However, when this particular phone belongs to a friend, we actually need to exert cognitive control to inhibit this habit and perform the goal-directed action of alerting our friend to pick up.

Classically, cognitive control is attributed to a supervisory, general-purpose system (e.g., Norman & Shallice, 1986) that is associated with features such as voluntary (e.g., Bugg & Crump, 2012), domain-general (e.g., Kan et al., 2013), and conscious (e.g., Dehaene & Naccache, 2001; Evans & Stanovich, 2013; Kunde, Reuss, & Kiesel, 2012). Though useful for descriptive purposes, such conceptualization has one major drawback: It does not explain what drives cognitive control in the first place, and does little more than assigning all responsibility for goal-directed behavior to an unspecified intelligent agent. Over the last decades, computational models have started to develop a solution to this problem by making explicit and testing the principles underlying cognitive control and other higher-order processes (Botvinick & Cohen, 2014; O'Reilly, 2006; Silvetti & Verguts, 2012). With a touch of irony, this solution involves the implementation of cognitive control via its traditional counterpart: learning.

In the current paper we outline and review an associative learning perspective on cognitive control. The review is restricted to control functions that govern direct interactions with the external world, and in particular those resolving *action uncertainty*, because their popularity led to a large database in the last decade. We consider cases in which multiple response options are active (conflict adaptation); in which multiple task sets are active (task switching); in which execution and inhibition of a response are in competition (response inhibition); and in which multiple targets for attentional selection are available (attentional control). The overall purpose of our review is to provide a broad empirical and theoretical foundation for grounding cognitive control in associative learning.

## An Associative Learning Perspective on Cognitive Control

Associative learning is typically explored at S-S and S-R levels (e.g., classical and operant conditioning). However, learning may also occur for more abstract representations that modulate perceptual (S) and motor (R) representations to produce goal-directed action (Egner, 2014; Verguts & Notebaert, 2009; see also Logan, 1988). We here refer to the former as *goal representations*, which correspond to what Egner (2014) labeled as abstract features or what has been modeled as task demand units (e.g., Botvinick et al., 2001; Verguts & Notebaert, 2008). The notion that learning extends beyond the level of perceptual and/or motor representations is core to the associative learning perspective on cognitive control. Specifically, the perspective holds that perceptual, motor and goal representations that are coactivated during a specific task become bound to each other into an associative network (see Figure 1)— that thus codes the overall *context*.[1] This network subsequently enables cognitive control, as perceptual representations will trigger contextually appropriate control via associations with specific goal representations. For example, when a specific color becomes associated with the inhibition of a specific response, the mere appearance of an item containing this color feature triggers inhibition and thus implements control (cf. Figure 1, arrow 1). Naturally,
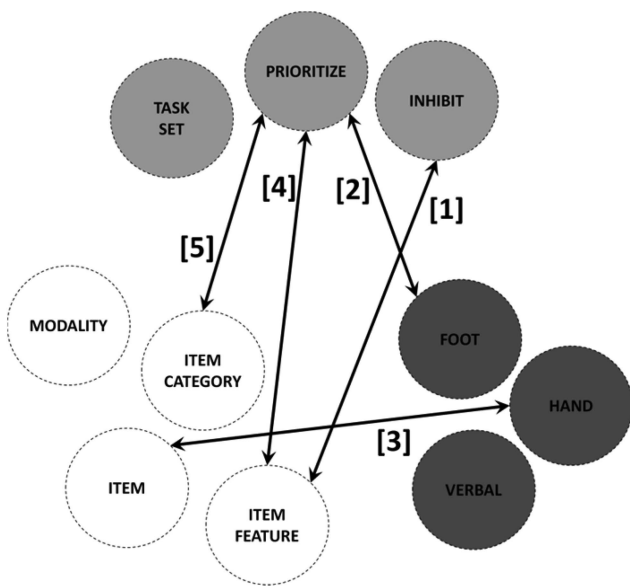


*Figure 1.* Illustration of an associative learning perspective on cognitive control. Cognitive control—like more classical S-R/S-S contingency learning—derives from association formation based on contingencies between perceptual (*white*), motor (*dark grey*), and goal representations (*light grey*). The goal representations that are depicted here relate to conflict adaptation and attentional control (prioritization), response inhibition (inhibition) and task switching (task set), but this is by no means exclusive or exhaustive. Five examples from the main text are illustrated: [1] response inhibition triggered by stimulus color (Boehler et al., 2012), [2] effector-specific conflict adaptation effects such as in Braem et al. (2011), [3] implementation of item-specific S-R contingency (Schmidt & Besner, 2008), [4] attentional capture primed by color (Cosman & Vecera, 2014), and [5] implementation of category-driven attention modulation (Cañadas et al., 2013).

relevant goal representations will differ between domains of cognitive control; for example, whereas conflict adaptation and attentional control may relate to the prioritization of a particular type of information, task switching and response inhibition may be related to the priming of specific task sets or inhibitory processes, respectively (cf. Figure 1).

Grounding cognitive control in associative learning dictates that the former shares the typical characteristics of the latter. Three core predictions can be made. First, *cognitive control should be context-specific*. The notion that control is enabled through the binding of all (and only) active representations into a network, necessarily limits the scope of control to these representations. Importantly, active but task-irrelevant representations also bind, and a more specific prediction thus holds that cognitive control and its transfer can be restricted by otherwise task-irrelevant features. Hence, context drives and restricts cognitive control.

Second, *cognitive control is predicted to operate in the absence (and presence) of awareness*. According to a large literature on implicit learning (e.g., Destrebecqz & Cleeremans, 2001; Jensen, Kirsch, Odmalm, Kaptchuk, & Ingvar, 2015; Nissen & Bullemer, 1987; Schmidt, Crump, Cheesman, & Besner, 2007; Seger, 1994; Seitz & Watanabe, 2005), associations between various types of representations can develop outside awareness. Moreover, once associations are in place, subliminally presented items can trigger their associated representations (e.g., Custers & Aarts, 2010). As such, cognitive control based on associative networks can operate in the absence of awareness.

Third, *cognitive control should be sensitive to reward*. The effects of reward on associative learning have been extensively documented (e.g., Schultz, 2002; Skinner, 1953; Thorndike, 1911). Reward provision is thought to reinforce S-R associations (i.e., the law of effect; Thorndike, 1911), dependent on midbrain dopamine modulation (e.g., Kelley, 2004; Robbins & Everitt, 1996; Schultz, 2002). From an associative learning perspective, then, cognitive control is predicted to be subject to reward, too.

Interestingly, the roles of context, awareness, and reward have developed into trending—though relatively independent—research themes in cognitive control. Indeed, this has been the case for each of the four major domains of cognitive control pinpointed above (conflict adaptation, task switching, response inhibition, and attentional control). This is no coincidence, we believe, as these themes reflect a (latent) growth of interest in learning-based control (cf. Egner, 2014). In the next section we review these themes, the structure of which is summarized in Table 1. The review demonstrates that the above three predictions are mostly confirmed and thus that the associative learning perspective offers broad-scaled integration for a large but scattered set of empirical observations. We elaborate on prototypical examples (cf. Table 1) and discuss how dominant (and domain-specific) theories and frameworks can be related to the associative learning perspective. Subsequently, in the section on "Challenges and Future Directions" we steer the

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[1] Throughout the paper the term "context" refers to the representations that are (or have been) active during a particular event, including both task-relevant and task-irrelevant information, and perceptual, motor, and goal representations. This slightly deviates from other uses of the term as in, for example, the work by Cohen and Servan-Schreiber (1992) or Braver and Barch (2002).

Table 1
*Overview of the Structure of the Review Presented in the Current Paper: Prototypical Example Studies are Briefly Described*

| Domain | Theme | | |
| --- | --- | --- | --- |
| | Context-specificity | Operation in the absence of awareness | Reward-sensitivity |
| Conflict adaptation (Table A1) | Congruency sequence effect in a Stroop task with verbally presented stimuli only occurs when irrelevant voice gender repeats (Spapé & Hommel, 2008). | Location-specific proportion congruency effect occurs without awareness of item (in)congruency or proportion congruency (Reuss et al., 2014). | Congruency sequence effect is enhanced following performance-contingent reward signals (Braem et al., 2012). |
| Task switching (Table A2) | Location-specific switch-proportion manipulation modulates the switch cost (Crump & Logan, 2010). | Subliminally presented cues that predicted task switches facilitate switching (Farooqui & Manly, 2015). | Switch costs are enhanced when the previous trial is rewarded (Umemoto & Holroyd, 2015). |
| Response inhibition (Table A3) | Irrelevant item features can become associated with and subsequently prime response inhibition (Giesen & Rothermund, 2014). | Slowing can be induced by unconscious processing of stop-signals (Van Gaal et al., 2009). | The stop-signal reaction time is smaller for rewarded than for unrewarded task-stimuli (Boehler et al., 2012). |
| Attentional control (Table A4) | Attentional set can be primed by task-irrelevant context (Cosman & Vecera, 2013). | Subliminally presented singleton can capture attention (Lamy et al., 2015). | Attentional capture is stronger for items associated with reward (Hickey & van Zoest, 2012). |

associative learning perspective into new territory and discuss some major challenges ahead.

## Associative Learning in Cognitive Control: A Review

We conducted literature searches through Web of Science. For the period 2005 through 2015 and for the research areas Psychology, Behavioral Sciences, and Neurosciences & Neurology, we inserted combinations of key words that cross the four domains and three research themes that are at the core of the current paper (see footnotes of Appendix A Tables A1 through A4). Several restrictions were imposed to maintain a clear focus. First, only behavioral studies on healthy young adults were included. Second, we zoomed in on a selection of major phenomena for each cognitive control domain (Conflict adaptation: *congruency sequence and proportion congruency effects*; Task switching: *switch costs and task priming effects*; Response inhibition: *go/no-go and stop-signal performance*; Attentional control: *visuospatial attentional capture*). For these phenomena we considered studies that addressed the roles of context, awareness, and reward in cognitive control. Third, for context-specificity we left out training and transfer studies with a more applied focus (but see the section below entitled "Beyond basic paradigms"), or with a focus on affective context. Fourth, with respect to reward, we only considered studies investigating the effects of reward feedback (but not punishment or omission) because of its clear link to (reinforcement) learning, and we thus excluded studies on reward cuing.

From the (relevant) papers obtained with these key words and restrictions we used the reference lists to further complete the database and also added a small number (<10) of papers that we knew to be relevant but did not come up in the search. The overall results of the literature searches are documented separately for each cognitive control domain in Appendix A Tables A1 through A4.[2] These tables provide the empirical backbone to the associative learning perspective that we outline and defend in the current

paper. Portions of these tables are detailed and discussed in the main text to illustrate this perspective. Finally, in our review section we discuss various additional papers (also from before 2005) that contained important insights about, or could be reinterpreted in terms of, the link between cognitive control and associative learning (not included in Tables A1 through A4).

In the review below we first focus on conflict adaptation, because here the link between learning and cognitive control has been discussed most extensively. Subsequently, we consider task switching, response inhibition, and attentional control. Despite being presented as separate review sections, the parallel investigation of context, awareness and reward across these four domains, and the conceptual link to associative learning as a shared underlying mechanism, brings these sections together.

## Conflict Adaptation

To maintain goal-directed behavior, we need to protect ourselves from cognitive *conflict*, which refers to interference by distracting information and/or prepotent response options that are incompatible with current goals. In the lab, overcoming conflict is typically studied in conflict tasks such as the Stroop task (Stroop, 1935; Figure 2A). This task requires naming the ink color of color words, and responses are typically faster and/or more accurate when the ink color is compatible rather than incompatible with the word meaning. This performance difference is referred to as the congruency effect, and is taken as an index of control: Larger congruency effects imply less cognitive control. Other well-known

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[2] In these tables we added "yes" or "no" to indicate whether or not a study outcome aligns with the prediction of the associative learning perspective. Notably, while those studies indicating some sort of generalization of control are indicated to *not* align with context-specificity in these tables, we argue in the section on "Generalization" below paper that substantial generalization can still derive from context-specific learning.
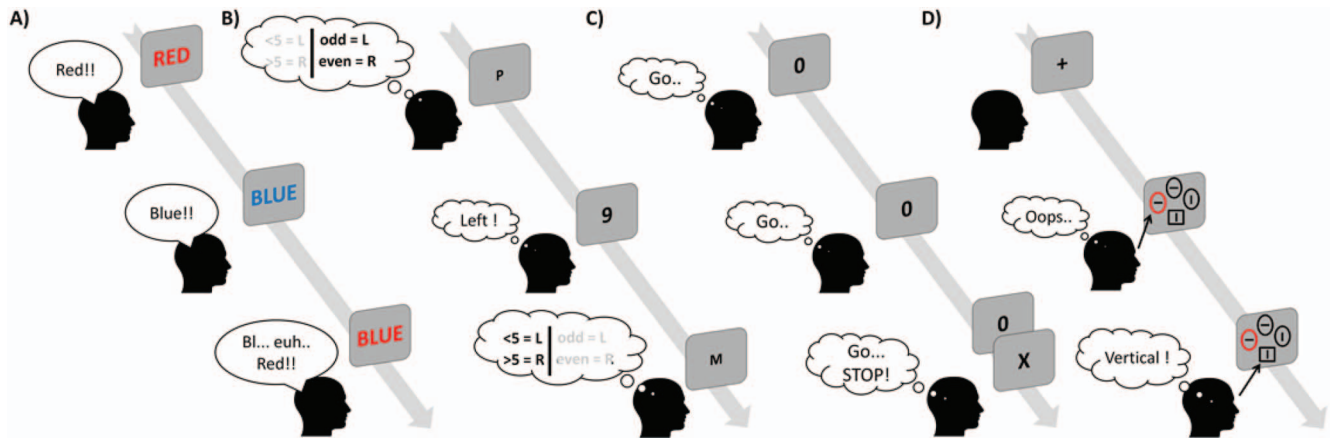
*Figure 2.* (A) Basic paradigm from the conflict adaptation domain (Stroop task; three trials). The task is to name out loud the ink-color while ignoring the color-word, but performance differences between congruent and incongruent pairings of ink-color and color-word (i.e., congruency effect) indicate that the color-word is not fully ignored. Responses can also be manual. (B) Basic paradigm from the task switching domain. Magnitude (item smaller or larger than 5?) and parity (item odd or even?) tasks are intermixed such that switching between task sets is required. Tasks are either precued on each trial (in this example: cue 'M' for magnitude task, then target item '9,' and finally cue 'P' for a switch to parity task), or follow a fixed task sequence (e.g., AABBAA) with no precues required. Responses are typically manual (not depicted). (C) Basic paradigm from the response inhibition domain (Stop-signal task; three trials). Response has to be executed upon presentation of a go stimulus (here: 0), while cancelation of execution is required on a proportion of trials on which the go stimulus is quickly followed by a stop-signal (here: X). Responses are typically manual (not depicted). (D) Basic paradigm from the attentional control domain (additional singleton task; a single trial). The task is to determine the orientation of the line segment within the target shape singleton while overcoming distraction from the salient color singleton. Responses are typically manual (not depicted). See the online article for the color version of this figure.

conflict tasks are the flanker and Simon tasks, in which participants respond to the identity of a target item while experiencing facilitation or interference either from distractor items that flank the target (flanker task; Eriksen & Eriksen, 1974) or from the task-irrelevant item location (Simon task; Simon & Rudell, 1967).

Over the last decades, researchers have developed an interest in the observation that the congruency effect can be modulated in response to *recent* and *frequent* conflict. Specifically, the congruency effect is reduced both following an incongruent trial (i.e., congruency sequence effect or CSE), and with high proportions of incongruent trials over longer periods of time (i.e., proportion congruency effect). These modulations of *attentional settings* in response to changing environmental demands are referred to as conflict adaptation (Botvinick et al., 2001).

The domain of conflict adaptation offers a seminal example of how goal-directed behavior could be rooted in learning. Building on a rich history of earlier models (Braver & Cohen, 2000; Cohen, Dunbar, & McClelland, 1990), Botvinick and colleagues proposed their highly influential conflict monitoring theory (Botvinick et al., 2001; Botvinick, Cohen, & Carter, 2004). Inspired by classical methods for parameter estimation (i.e., learning; Robbins & Monro, 1951) that are frequently used in the psychology of learning (e.g., Behrens, Woolrich, Walton, & Rushworth, 2007; Rescorla & Wagner, 1972), conflict monitoring theory explains how a cognitive agent determines *when* there is a need for enhanced prioritization of relevant information. Specifically, an evaluative system—the conflict monitor—continuously learns the average level of conflict in the current task (Botvinick et al., 2001; their

Equation 2), and signals the need for enhanced control when estimated conflict is large.

The conflict monitoring theory suggests how the cognitive control system determines when to intervene. However, it does not specify how the system determines *where* to intervene (cf. Botvinick & Cohen, 2014). The adaptation-by-binding model by Verguts and Notebaert (2008, 2009) proposed a possible solution to this challenge: *Associative (Hebbian) learning* between perceptual, motor, and goal representations implements adaptations to conflict. In this model, conflict detection results in a catecholamine boost (noradrenaline or dopamine) across cortex that facilitates ongoing Hebbian learning and thus the binding of currently active representations. Because active representations are usually task-relevant, conflict detection enhances binding of task-relevant representations—thereby enhancing control. Verguts and Notebaert (2008) showed that such a learning mechanism can account for both CSEs and proportion congruency effects. Overall, these models demonstrate how formulating conflict adaptation as a learning problem can help understanding cognitive control in a self-regulating and thus homunculus-free manner.

**Context-specificity.** A current debate centers on whether adaptation to conflict derives from domain-general or domain-specific mechanisms (e.g., Braem, Abrahamse, Duthoo, & Notebaert, 2014; Egner, 2008). Traditionally, conflict was assumed to be detected by a single, domain-general conflict detector that subsequently enhances generic control. In contrast, CSEs have been found to be highly domain-specific (Table A1; for exceptions see Generalization section). For example, when combining trials

from Simon and Stroop tasks, Egner, Delano, and Hirsch (2007) observed a CSE for task repetitions but not for alternations. This lack of transfer between tasks suggests domain-specificity. Egner (2008) proposed that multiple conflict–control loops operate independently from each other, with one type of conflict (e.g., perceptual conflict in the Stroop task) being detected and managed by a different conflict-control loop than another type of conflict (e.g., response conflict as in the Simon task). This proposal prompts the question about how such conflict-control loops evolve. It would be biologically implausible to assume a large number of preexisting conflict-control loops ready for use. Instead, the associative learning perspective on cognitive control suggests that by binding all active associations, conflict adaptation relies on a general learning mechanism that nonetheless results in highly specific adaptations.

Associative learning also allows integrating related findings. CSEs are specific not only to conflict-type but also to various task-irrelevant features (Table A1). For example, in an auditory Stroop task with spoken words as distractor items, Spapé and Hommel (2008) observed a CSE only if the irrelevant voice gender repeated between trials. Similarly, Braem, Hickey, Duthoo, and Notebaert (2014) demonstrated how the CSE in a flanker task only occurred when a salient, but task-irrelevant, color surrounding the task item repeated. Finally, it has been shown that the CSE depends on the effector set, as no CSE was observed when previous and current trials required different effectors (Figure 1, arrow 2; e.g., Akcay & Hazeltine, 2008; Braem, Verguts, & Notebaert, 2011; Kim & Cho, 2014). These conflict- and context-specific observations fit nicely with the idea that goal representations (underlying attention modulation) become associated with contextual features. Indeed, the impact of salient but irrelevant context on conflict adaptation such as in the studies by Spapé and Hommel (2008) and Braem et al. (2014), is one of the major testable predictions that are more specific to an associative learning perspective.

Proportion congruency was initially manipulated list-wide (i.e., list-wide proportion congruency effect, or LWPC effect; e.g., Logan & Zbrodoff, 1979), and assumed to trigger domain-general attention modulation by a supervisory system. Later findings, however, demonstrated that proportion congruency effects can develop separately for specific contexts such as screen location (e.g., Crump, Gong, & Milliken, 2006) or background shape (e.g., Schouppe, Ridderinkhof, Verguts, & Notebaert, 2014)—which importantly are *randomly* mixed across trials. Indeed, in their seminal paper, Jacoby, Lindsay and Hessels (2003) even showed that this works for item sets with distinct proportions of congruency. These context-specific (CSPC) and item-specific proportion congruency (ISPC) effects are highly robust and replicable (Table A1), and refute domain-general attention modulation. They instead suggest rapid and transient attentional shifts based on trial context, in line with the associative learning perspective: Robust associations between perceptual and goal representations are formed when they covary, such that upon future presentation the former can rapidly trigger the latter.

For both CSEs and proportion congruency effects, recent debates have pitted learning and conflict adaptation against each other. Specifically, various learning-based alternatives have been proposed to explain the typical data patterns taken to support conflict adaptation—and these alternatives do not involve attention

modulation. Major examples are feature integration and contingency learning accounts. The former states that the CSE can be explained by the costs of partial repetitions of item and/or response features—which are more frequent for congruency alternations than congruency repetitions (e.g., Mayr, Awh, & Laurey, 2003; Hommel, Proctor, & Vu, 2004). The latter adds that designs are typically confounded by S-R contingency learning processes and their mutual interactions, which can produce data patterns that resemble CSE and proportion congruency effects (e.g., Mordkoff, 2012; Schmidt & De Houwer, 2011; Schmidt, 2013a,b).

Independent of the empirical status of this debate (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014; Schmidt, 2013b), we argue that its core premise is flawed. Specifically, from the associative learning perspective neither feature binding nor S-R contingency learning are true theoretical alternatives to conflict adaptation, as each derives from similar associative learning (or binding) mechanisms. What is learned in conflict adaptation are goal-response or goal-item associations that result in enhanced attention to relevant information upon contextual demand—and these associations are learned in parallel with S-R (or S-S) associations. To illustrate this relationship, Figure 1 (arrow 3) includes an example of an S-R contingency learning study (Schmidt & Besner, 2008) amidst (other) cognitive control studies.

**Operation in the absence of awareness.** Cognitive control is traditionally associated with conscious processing (e.g., Baars, 1993; Dehaene & Naccache, 2001; Mayr, 2004; Posner & Snyder, 1975; Schneider & Shiffrin, 1977; Umilta, 1988), partly inspired by their shared link to prefrontal cortex (Botvinick et al., 2001; Dehaene & Changeux, 2011; Lau & Rosenthal, 2011). In contrast, the associative learning perspective predicts cognitive control to operate also in the absence of awareness, and recent proportion congruency and CSE studies have confirmed this empirically (Table A1). For example, Blais, Harris, Guerrero, and Bunge, (2012) investigated whether one needs to be aware of the proportion congruency manipulation in order for it to modulate attention. The authors presented several item lists with different proportions of congruent items, and after each list asked participants to estimate the proportion congruency of the most recently finished list to index awareness. The proportion congruency effect developed independently from the proportion congruency awareness. Similarly, Reuss, Desender, Kiesel, and Kunde (2014) showed reliable CSPC effects in the absence of awareness of both conflict and context cues.

For trial-by-trial manipulations such as the CSE, support for the notion of unconscious adaptation was initially lacking. In his seminal study, for example, Kunde (2003) observed no CSE in a prime-target task when primes were subliminally presented. Yet, the weight of more recent evidence leans toward confirmation as conflict adaptation outside awareness has been systematically observed in prime-target tasks (Table A1; Desender, Van Lierde, & Van den Bussche, 2013). Note that from the associative learning perspective, CSEs (and also proportion congruency effects) may still be weaker for unconscious than conscious items, simply because of reduced stimulus strength (Dehaene & Naccache, 2001). This may explain why, for example, Desender, Van Opstal, and Van den Bussche (2014) observed that the CSE was only present after trials on which participants reported to have experienced response conflict (cf. Abrahamse & Braem, 2015).

**Reward-sensitivity.** Recent studies have explored the impact of reward on performance in conflict tasks (Dreisbach & Fischer, 2012). Several studies explored how the congruency effect is affected by reward expectancy—and thus motivation (e.g., Krebs, Boehler, & Woldorff, 2010; Soutschek, Strobach, & Schubert, 2014). For example, Soutschek and colleagues (2014) demonstrated that expectancy both of high reward and high conflict reduced the Stroop effect. Furthermore, in high reward expectancy blocks (i.e., high motivation) the degree of conflict expectancy had no additional impact on conflict processing. The authors concluded that reward and conflict expectancy engage similar processes. Indeed, higher reward expectancy may accelerate learning, resulting in strengthened task-relevant associations.

Especially important for present purposes are studies that focused on reward feedback (i.e., reinforcement learning; see Table A1). Most of these studies showed that conflict adaptation can indeed be modulated by reward provision, but results are not unequivocal. For example, while Van Steenbergen and colleagues (Van Steenbergen, Band, & Hommel, 2009, 2012) observed that randomly provided affective reward items eliminated the CSE, other studies showed that performance-contingent reward enhanced the CSE (e.g., Braem, Verguts, Roggeman, & Notebaert, 2012; Stürmer, Nigbur, Schacht, & Sommer, 2011). This apparent contrast may derive from the fact that only performance-contingent reward acts as a reinforcement signal, resulting in adaptation through strengthened connections between task representations and the response (Dreisbach & Fischer, 2012). We return to this issue in the section below on "Computational Integration."

**Summing up conflict adaptation.** The last two decades have resulted in a substantial empirical database on conflict adaptation, related to its context-specificity, its operation in the absence of awareness, or its sensitivity to reward (Table A1). What has been lacking is an integrated framing and synthesis. We here integrate these observations by linking them to associative learning. A clear theoretical advantage of an associative learning perspective is that it allows reconceptualizing current debates in the literature. For example, rather than opposing conflict adaptation and S-R contingency learning, both should be considered as instances of associative learning. This perspective can also help in understanding conflict adaptation without the need for an elusive homunculus, because the learned context drives conflict adaptation. In this respect, especially the impact of task-irrelevant context on conflict adaptation (e.g., Spapé & Hommel, 2008) supports the associative learning perspective and its activation-based mechanism (i.e., all and only active representations are involved). There remain some clear challenges, though, such as the transfer effects of conflict adaptation across item sets and/or tasks. These will be discussed below in the section on "Generalization." Moreover, a number of straightforward predictions remain to be tested; for example, the CSPC and ISPC effects are predicted to be modulated by reward provision.

Besides integration within the specific domain of conflict adaptation, the associative learning perspective also has much to offer in other domains of action control. In the next section we turn to task switching. Although conflict adaptation and task switching seem to address conceptually different challenges—namely, a need for stability versus flexibility, respectively—we will show that similar ideas and key observations have emerged across both

domains. We will argue that this is attributable to shared underlying principles.

## Task Switching

Cognitive agents need to continuously implement and switch between specific task sets to enable goal-directed action. In the lab, this can be explored by providing participants with two or more different task sets (i.e., S-R mappings) and require them to switch frequently between these task sets (see Figure 2B). We now explore associative learning for (task) switch costs and related effects, as well as for task priming effects (Table A2).

**Context-specificity.** An important empirical measure in the task switching literature is the switch cost: The cost in RTs or accuracy associated with switching relative to repeating tasks. Meiran (1996) suggested a dissociation between bottom-up and top-down forces in the switch cost by showing that with increased preparation time the switch costs can be diminished. This finding is often interpreted as uncovering a top-down reconfiguration of the cognitive system to prepare for the upcoming task. However, there typically remains a residual switch cost regardless of preparation time. This is often attributed to bottom-up interference (cf. Allport, Styles, & Hsieh, 1994; Yeung & Monsell, 2003a, 2003b). Indeed, Vandierendonck, Liefooghe, and Verbruggen (2010) concluded from their review that "task-set preparation must be both reconfiguration and interference control if it is to explain the extant evidence regarding preparation-related switch costs" (p. 618).

From an associative learning perspective, the reconfiguration and interference accounts would be similarly implemented and thus require little further integration. For successful performance on one Task A, several contextual representations are activated across the perceptual, motor, and goal levels. The resulting associative network (including salient but irrelevant item features) facilitates future performance on this task. For example, specific items can trigger specific task sets with which they have been systematically associated (e.g., Gade & Koch, 2007; Katzir, Ori, Hsieh, & Meiran, 2015; Koch, Prinz, & Allport, 2005; Waszak & Hommel, 2007). We can further assume lateral, competitive inhibition between representations *within* a particular level; for example, goal representations underlying Tasks A and B mutually inhibit each other (Munakata et al., 2011). Consequently, at the time of activating Task A, associations between goal and other context representations for Task B may weaken due to anti-Hebbian learning (i.e., unlearning of an association), and performance is impaired on future presentations of this task. Together, activation and lateral inhibition provide a benefit when the same task has to be performed again, but a cost for an alternation.

More direct support for an associative account of the switch cost was provided by Leboe, Wong, Crump, and Stobbe (2008) and Crump and Logan (2010). In their studies, the authors showed that switch costs can be modulated by rendering item features (e.g., location) predictive of proportion task switch versus repetition: Items presented at the location associated with a high proportion of switches resulted in reduced switch costs. This indicates context-specific control over task-setting processes.

Interestingly, switch costs interact with previous-trial congruency, in the sense that switch costs are larger following incongruent trials (i.e., conflict-modulated task-switch cost, Goschke, 2000), or more difficult tasks in general (i.e., asymmetric task-

switch cost, Allport et al., 1994). Such an interaction calls for a shared mechanism, and the associative learning perspective may offer this. Hence, conflict-modulated task-switch cost can be explained by assuming that after incongruent trials, associations between item and goal representations are strengthened more than after congruent trials (i.e., conflict-induced boost in learning; cf. Verguts & Notebaert, 2008), and this benefits task repetitions but hinders task switching.

Research has also shown an impact of the penultimate on the current trial. Backward inhibition (Mayr & Keele, 2000; Koch, Gade, Schuch, & Philipp, 2010) refers to the reaction time cost following the return to a recently abandoned task (*ABA* task sequence) compared with the return to a task not recently performed (*ABC* task sequence). Backward inhibition, too, can be accounted for by associative learning. The residual activation of Task A is high while performing Task B because it is the most recently activated task. Previous-trial activation will be inhibited due to anti-Hebbian learning, and crucially will affect Task A *more* than Task C. As a consequence, when performing Task A on the next trial, performance is impaired relative to Task C. A similar mechanism can account for reversed CSEs on task alternations (e.g., Braem et al., 2011; Notebaert & Verguts, 2008).

Finally, and reminiscent of the debates in the domain of conflict adaptation, the associative learning perspective may unify what are typically held as strong dichotomies (cf. reconfiguration vs. interference; see above). For example, response congruency effects (i.e., impaired performance for target items associated with different as compared to same responses across tasks) have been the subject of discussion as to whether they reflect interference from a mediated or a nonmediated route (e.g., Schneider, 2015). The former involves task categorization whereas the latter builds on previously experienced S-R associations. From the associative learning perspective these routes are not that different as both involve learning across perceptual, motor, and/or goal levels. Similar arguments can be made for response repetition (i.e., response repetition benefits reverse for task alternations; Kleinsorge & Heuer, 1999) and cue-switching effects (i.e., cue switching impedes performance even when the task remains the same; e.g., Logan & Bundesen, 2003). Whereas much of the current literature opposes learning versus nonlearning explanations, the associative learning perspective understands both observations as reflecting the aftereffects of binding between perceptual, motor, and goal representations.

**Operation in the absence of awareness.** Task selection—a major aspect of task switching—is possible without awareness when task sets are contextually primed. For example, Lau and Passingham (2007) explored the switching between phonological and semantic judgment tasks. On some trials, participants were visually primed with the instruction to perform the alternative task, and this reliably impaired performance. Importantly, this impairment was also present when participants could not discriminate prime identity above chance level. Besides supporting the notion of contextual triggering of a task set (see above), such unconscious activation of task set suggests that consciousness is not necessary for task selection. Whenever a prime is associated with a goal representation (in this case a task set), it can activate its corresponding goal representation even when the prime is presented subliminally. This has been replicated in numerous studies (Table A2). Interestingly, more abstract task processes, too, can be contextually triggered outside awareness. For example, Crump and Logan (2010) observed location-based control over task set effect (see

above) even when subjects were unaware of the relationship between item location and switch likelihood. Moreover, Farooqui and Manly (2015) explored switch costs in a similar manner, but instead presented subliminal cues indicating switch likelihood. They also observed a modulation of the switch cost in the absence of awareness.

**Reward-sensitivity.** Reward modulates task switching (Table A2). For example, Umemoto and Holroyd (2015) demonstrated how switch costs are enhanced when the previous trial is rewarded, relative to when it is not. This suggests that reward boosts associations between perceptual and goal representations that underlie switch costs (see above). Similarly, Braem et al. (2012; Exp. 2) showed that reward modulates the conflict-modulated task-switch cost (Goschke, 2000; see above): Switch costs were largest following incongruent trials when this previous trial was also rewarded. Finally, Jiang and Xu (2014) observed that reward can enhance backward inhibition in task switching. When the previous (i.e., $n - 1$) trial was rewarded, increased backward inhibition was observed (i.e., larger impact of trial $n - 2$ on trial $n$). This suggests that the anti-Hebbian learning that negatively affected Task A when switching to Task B in an ABA task sequence was enhanced due to the reward that followed Task B.

**Summing up task switching.** Task selection and switching are possible in a contextually driven and unconscious manner—consistent with associative learning (Table A2). Indeed, several seminal observations may be reinterpreted in terms of associative learning, such as the switch cost and backward inhibition. Such reinterpretation is indirectly supported by their reward modulation. The associative learning perspective thus connects several task switching phenomena, and in a broader sense links these to other aspects of cognitive control such as the above-discussed domain of conflict adaptation. Indeed, a shared foundation can account for observed interactions between these control domains such as the conflict-modulated task-switch cost. Moreover, an associative learning perspective allows reconceptualizing longstanding debates in task switching in which control and/or learning alternatives are (unnecessarily) contrasted. Importantly, the impact of salient but irrelevant context remains underexplored in this domain (but see Rubin & Koch, 2006). Would a cost occur when the same task is repeated in different irrelevant contexts? Exploration of these issues would further test the viability of an associative learning perspective in task switching.

In the next section we continue with the domain of response inhibition. The specialized experimental paradigms for response inhibition, too, have targeted the research themes discussed above for conflict adaptation and task switching.

## Response Inhibition

Fostering goal-directed behavior often involves the sudden need for inhibition of prepared or ongoing responses. This has resulted in extensive research on response inhibition; importantly, context-specificity, awareness-independence, and reward-sensitivity have all been observed in this domain (see Table A3). We discuss two major paradigms (the go/no-go and stop-signal tasks) and elaborate on a number of studies from Table A3 to illustrate the associative learning perspective in response inhibition.

**Context-specificity.** In the go/no-go task, participants respond to prespecified 'go' items, and withhold responding to prespecified 'no-go' items. In the standard version, the go and

no-go items are consistently associated with going and stopping, respectively, thus allowing for the formation of strong associations between an item and a control setting. Verbruggen and Logan (2008) explored this issue by switching the go and no-go items in a test phase (i.e., previous go items became no-go items and vice versa), after substantial training on the initial mapping. They observed that this change slowed responding in the test phase. Similarly, Anderson and Folk (2012) showed with a go/no-go version of the flanker task that irrelevant flankers presented in the color associated with a no-go item inhibit specific target responses. These results suggest that direct associations are formed between the perceptual, motor, and goal representations (cf. Figure 1; cf. Parkinson & Haggard, 2014).

Similar findings exist for the stop-signal task. This task requires participants to perform speeded choice reactions, but occasionally, the target is followed by a prespecified stop-signal that instructs the participant to withhold the response (Figure 2C). Successfully withholding the response is only achieved when the stop-signal follows sufficiently fast. In contrast to the go/no-go task, the target items in the typical stop-signal task are equally associated with going and stopping, as all can be followed by a stop-signal with equal probability. Still, learned inhibition has been demonstrated in this task. For example, in an adapted version of the task, Verbruggen, Best, Bowditch, Stevens, and McLaren (2014; their Appendix A) showed that items that were earlier systematically presented in stop-trials were responded to slower when now presented in a go-trial (but see their Appendix B). This indicates associative learning between items and response inhibition such that the former can drive the latter (cf. Lenartowicz, Verbruggen, Logan, & Poldrack, 2011; Upton, Enticott, Croft, Cooper, & Fitzgerald, 2010; Vallesi, Hasher, & Stuss, 2010). Interestingly, Giesen and Rothermund (2014) showed that such links between item features and goal representations can develop even when the feature is otherwise task-irrelevant.

Bissett and Logan (2012) showed that response inhibition improved at the second of two consecutive stop-trials when stop-signals were exactly the same, whereas such enhancement was absent with stop-signals from different modalities. The latter illustrates how learning restricts the scope of control, as control is specific to the associations that developed. Indeed, go/no-go task training improves inhibitory control on the trained task but (despite item overlap) does not transfer to other inhibitory control tasks (e.g., stop-signal task; Thorell et al. 2009). This is in line with the notion that go/no-go and stop-signal tasks involve distinct inhibitory control mechanisms and representations (Aron, 2011; Swick, Ashley, & Turken, 2011).

**Operation in the absence of awareness.** Response inhibition can operate in the absence of awareness. Van Gaal, Ridderinkhof, Scholte, and Lamme (2010) demonstrated that an unconsciously perceived no-go item can activate prefrontal inhibitory networks, and that such an item slows down performance but does not stop it—as if inhibition was initiated but failed to fully withhold responding. From the current perspective, once associations have formed between an item and a goal representation (i.e., response inhibition) the item can activate its associated goal representation even when presented subliminally.

Additionally, a study by Van Gaal, Lamme, Fahrenfort, and Ridderinkhof (2011) demonstrated that a subliminally presented

stop-signal ("STOP") can become increasingly associated with—and thus prime—response inhibition over the course of a single experiment. These authors employed a stop-signal task in which the stop-signal was either just visible (i.e., suboptimal masking) or subliminal (optimal masking). It was observed that subliminally presented stop-signals—which were probably not fully semantically processed—could slow down subsequent noninhibited responses. Importantly, these effects increased with training, as if associations needed to form between the physical properties of the stop-signal and the goal to inhibit the response before subliminally presented stop-signals could impact performance. Hence, once the task-relevant inhibition network is in place, even subliminally presented information can activate it.

**Reward-sensitivity.** Response inhibition can be promoted by reward within the ongoing trial (Boehler, Hopf, Stoppel, & Krebs, 2012). Boehler and colleagues (2012) used a stop-signal task with two differently colored stop signals, one indicating reward for successful stop-performance and the other always being unrewarded. Response inhibition performance was significantly improved for the rewarded stop-signals. Because the two stop-signals were randomly intermixed, and stopping is implemented rapidly (around 200 ms after item onset), this strongly indicates that the two items differentially primed response inhibition. This was further supported by a second phase where no reward could be obtained and in which only go items were presented, in the previously rewarded stop-color, the nonrewarded stop-color, or the previous go-color. RTs were significantly slower on the previously rewarded stop color relative to the other two colors (but see Boehler, Schevernels, Hopf, Stoppel, & Krebs, 2014), in line with a reward-modulated association between a color and response inhibition (cf. Figure 1, arrow 1).

**Summing up response inhibition.** Our review exposes close parallels between the response inhibition literature and the domains of conflict adaptation and task switching, in the sense that the impact of context and reward has been demonstrated, while awareness is not crucial (Table A3). Importantly, and reminiscent of the domain of conflict adaptation, it has been shown that salient but task-irrelevant dimensions such as modality impact the scope of control (e.g., Bissett & Logan, 2012), and that otherwise task-irrelevant features can prime inhibition (Giesen and Rothermund, 2014). Such results point toward a major role of associative learning in response inhibition as it can account for the impact of task-irrelevant aspects.

In the next and final review section we zoom in on attentional control. In this domain it is investigated what mechanisms control the orienting of attention, mostly across the visual field. As with the other domains, this research is typically tied to a few specialized experimental paradigms, but again we can see similar research themes as for the other domains emerge in the attentional control literature.

## Attentional Control

In attentional capture paradigms participants respond to a predefined target among distractor items while attention is exogenously manipulated toward or away from the target (e.g., visual search performance can be modulated by presenting a distractor item that contains a unique feature [additional singleton; see Figure 2D], which can capture attention and delay search success).

Another method to capture attention is via abrupt onset cues (e.g., Posner, 1980; Theeuwes, 1991; Yantis & Jonides, 1984). Presenting onset cues nearby or on the subsequent target location (as compared to nontarget locations) has been shown to facilitate performance.

The impact of additional singletons or onset cues on performance is used to explore the interactions between top-down and bottom-up control in the attentional selection of information. Top-down selection occurs via an attentional set that defines the relevant information (Folk & Remington, 1998, 2006, 2008; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wu, 2009). Because an agent is constantly bombarded with sensory information, such goal-driven selection is crucial to prevent overload. However, (distractor) items can also automatically capture attention (Belopolsky, Kramer, & Theeuwes, 2005; Franconeri, Simons, & Junge, 2004; Theeuwes, 1991; Wolfe, 1994; Yantis, 1993). This bottom-up control involves capture by onset or otherwise physically salient items (i.e., salience-based attentional capture), or by otherwise task-irrelevant items that contain goal-related features (i.e., contingent attentional capture; Folk et al., 1992). Such capture may be crucial to detect unexpected but potentially relevant information.

**Context-specificity.** Contingent attentional capture can be considered an example of context-specific attentional control. When a feature is task-relevant, it becomes associated with goal representations that underlie, for example, the prioritization of this type of information or the location from which it is presented. These associations will trigger the goal representations whenever the feature is perceived, even when part of an irrelevant item. Indeed, singleton capture effects are highly specific to current (task) goal representations (e.g., Eimer & Kiss, 2010; Kiss & Eimer, 2011). Further examples of context-specificity may be the classical studies by Wolfe, Butcher, Lee, and Hyle (2003) and Maljkovic and Nakayama (1994). Here, participants first identify the target item on the basis of a 'pop-out' feature (e.g., search the uniquely colored item), and then respond according to another feature of this target item (e.g., is it truncated on the left or the right?). Wolfe and colleagues (2003) showed that search performance was impaired for trial-by-trial varying target-defining 'pop-out' features relative to blocks with stable target-defining 'pop-out' features, and explained this mainly in terms of more focused and efficient top-down orienting in the latter blocks. Maljkovic and Nakayama (1994) reported a related observation: Repetition of a specific 'pop-out' feature improves search relative to alternation, even when the next 'pop-out' feature is fully predictable. Interestingly, Maljkovic and Nakayama (1994) forwarded an explanation in terms of passive priming rather than top-down orienting. From the associative learning perspective, such top-down and bottom-up accounts are not necessarily true theoretical alternatives. Both build on the formation of associations between active perceptual and goal representations (e.g., prioritize a specific feature or information from a specific location)—with association strength being enhanced with each repetition. Accordingly, the impact of repeating the 'pop-out' feature has been observed to be largest when also the task (Thomson & Milliken, 2011) and task-irrelevant features (Huang, Holcombe & Pashler, 2004) repeat.

A number of recent studies further explored the role of context (Table A4). For example, Gough, Garcia, Torres-Quesada, and Milliken (2014) showed that exogenous orienting can be modu-

lated by the context-specific proportion of validly cued trials. This shows that attentional control can be directly steered by (formally) irrelevant contextual features, in strong analogy to what was discussed above for the other domains. Similarly, Cosman and Vecera (2013) showed that different attentional sets can be primed (i.e., activated) by different contexts. Participants were trained on contingencies between specific attentional sets (i.e., singleton-search vs. feature-search) and task-irrelevant background. It was observed that attentional capture by a salient distractor was modulated by these contingencies: Reinstatement of the background associated with feature detection resulted in smaller attentional capture effects. This again indicates a clear link between associative learning and attentional set selection. Interestingly, Cosman and Vecera (2013) demonstrated that amnesic patients show no influence of past experience on the instantiation of an attentional set.

Finally, several attentional capture studies considered contextually triggered inhibition. First, capture by an onset cue that is usually (or even always) counterproductive could only be resisted after experience with the task (Vecera, Cosman, Vatterott, & Roper, 2014), as if the onset cue needed to become associated with inhibition (cf. Zehetleitner, Goschy, & Müller, 2012). Second, Goschy, Bakos, Müller, and Zehetleitner (2014) showed in a visual search task that distraction by irrelevant singletons was reduced when they were presented in regions of the display with a higher probability of distractor presentation. This suggests that location can directly trigger inhibition of (feature) processing.

**Operation in the absence of awareness.** The impact of context on attentional set can also develop outside awareness. Cosman and Vecera (2014) showed that implicitly learned associations between a search target and its likely color modulate the ability of a salient color precue to capture attention in a classic attentional capture task—with larger attention capture when the precue matches the likely target color. This indicates that attentional control is set in the absence of awareness attributable to, for example, the activation of a goal representation (e.g., prioritize) that results from its associations with perceptual representations (e.g., color; cf. Figure 1, arrow 4). Additionally, it has repeatedly been shown that capture can occur via items that are not consciously perceived (Table A4). For example, Lamy, Alon, Carmel, and Shalev (2015) employed a color-singleton distractor as a spatial cue. It was observed that when this singleton was presented subliminally using continuous flash suppression, it could still capture attention when it matched the participants' current attentional set.

**Reward-sensitivity.** Reward history affects attentional selection independent of current goals or item saliency (Table A4; for a review see Anderson, 2013). Irrelevant and nonsalient item features that were previously associated with reward have enhanced potential to directly capture attention even when participants are aware that this is not beneficial to task performance (e.g., Anderson, Laurent, & Yantis, 2011a; Hickey & van Zoest, 2012). In the study by Hickey and Van Zoest (2012), for example, participants performed a saccadic selection task in which the goal was to perform a saccade to a target item above or below fixation. At each trial, a distractor was presented slightly to the left or right of the direct path between fixation and the target. Target and distractor items were red and green respectively (or vice versa) and color was irrelevant. Typically, in this task the distractor modulates the trajectory of target-directed saccades. Hickey and Van

Zoest (2012) combined this task with reward and observed that the distractor captured attention more strongly when it was presented in the color of the target on the previous trial, but especially when this previous trial was followed by a high relative to low reward. Interestingly, this attentional capture by previously rewarded item features depends on whether or not it has been rewarded in the same context as in which it currently appears (Anderson, 2015).

The impact of reward on attentional control is reminiscent of the priming effects of Maljkovic and Nakayama (1994) mentioned above: They both are neither fully top-down (i.e., they cannot be counteracted by volition; Hickey & Van Zoest, 2012) nor fully bottom-up (i.e., they do not depend solely on the state of the current item). Awh, Belopolsky, and Theeuwes (2012) therefore suggested adding a third category to the top-down/bottom-up dichotomy, namely past selection history (i.e., learning), which was proposed to be ultimately integrated with current goals and salient information to determine selection. However, instead of a tripartite model with distinct and yet-to-be-integrated categories, observations may be more parsimoniously framed within an associative learning perspective in which top-down and bottom-up attentional control both originate from associations between perceptual and goal representations. First, top-down influences may be based on fast, instruction-based learning (see below), forming associations across a few or maybe even a single trial. Second, whenever associations develop between goal and perceptual representations, otherwise task-irrelevant items containing goal-related features capture attention (i.e., contingent attentional capture; Folk et al., 1992). This is because associations allow for bottom-up priming of those same goal representations that generate top-down attentional control. Third, these associations strengthen with repetition (e.g., Maljkovic & Nakayama, 1994) and/or reward (e.g., Hickey & Van Zoest, 2012) and thus include

past selection history in a straightforward manner. Accordingly, past selection effects are not under full volitional control (i.e., once associations are in place, activating the specific perceptual representations will directly result in activation at the goal level); moreover, not all of the effect resides in the current item itself. Fourth, strong links at the sensory level circumvent goal representations but attract attention (salience-based attentional capture). A nice demonstration of the latter may be attentional capture by abrupt onset cues, which seems to occur independent of specific task goals (Schreij, Theeuwes, & Olivers, 2010; Schoeberl, Fuchs, Theeuwes, & Ansorge, 2015). This may derive from phylogenetically older learning, which falls beyond the scope of the current paper (interestingly, though, phylogenetically acquired capture mechanisms may still be context-sensitive; Young, Brown, & Ambady, 2012).

To return to the study by Hickey and Van Zoest (2012), then, the initial modulation of saccade trajectory by distractors is based on salience-based attentional capture. When a target is processed, this binds the context (among which the target's color feature) with the prioritization of information at that location. Whenever a reward follows immediately, these bindings are strengthened such that the color feature (irrelevant but active) is now associated more strongly with the goal to prioritize it, and subsequently has enhanced potential for (contingent-capture-like) distraction. In this example, the top-down processes (activating the goal representation) and the impact of past selection history (reward provision) are directly integrated. Similarly, Vecera and colleagues (2014) argued in their experience-based attentional tuning framework that top-down and bottom-up control of attention are not a strict dichotomy but rather ends of a continuum—with task dynamics determining their relative contribution (cf. Table 2).

Table 2

*Conceptual Simplification by the Associative Learning Perspective With Respect to Prominent Dichotomies Across Various Domains of Cognitive Control*

| Domain (phenomenon) | Dichotomy | Reference | Associative learning perspective |
| --- | --- | --- | --- |
| Conflict adaptation (congruency sequence effect) | Binding/contingency learning versus Cognitive control | Botvinick et al. (2001)Hommel et al. (2004) Schmidt (2013b) | Cognitive control is based on contingency-based associative learning |
| Conflict adaptation (proportion congruency effect) | Context-driven control versus Domain-general control | Bugg & Crump (2012) | Both derive from associations across perceptual, motor, and goal representations |
| Task switching (switch cost) | Reconfiguration versus Interference control | Allport et al. (1994) Meiran (1996)Vandierendonck et al. (2010) | Both derive from associations across perceptual, motor, and goal representations |
| Task switching (response congruency effect) | Mediated route versus Nonmediated route | Schneider (2015) | For both routes, response congruency effects derive from similar associative learning processes |
| Response inhibition | Associative learning versus Inhibitory control | Verbruggen & Logan (2008) | Associative learning effects are a feature of—and do not oppose—inhibitory action control |
| Attentional control | Top-down attention versus Bottom-up attention versus Past selection history (e.g., reward) | Awh et al. (2012) | Goal representations underlying top-down attentional control are associated with perceptual and/or motor representations on the basis of past selection history and can thus be triggered in a bottom-up fashion |

**Summing up attentional control.** Similar to the previously discussed domains, attentional control is highly context-specific and reward-sensitive, and can occur outside awareness (Table A4). Besides capturing these three key characteristics, we believe that the associative learning perspective may also help integrating the dominant theoretical frameworks of attentional control (e.g., Awh et al., 2012; Vecera et al., 2014). Specifically, associative learning naturally captures the impacts of currently active goal representations as well as past history (e.g., repetition and reward effects) and—in contrast to the (domain-specific) proposals that currently dominate this domain—it does so from a single principle.

## Challenges and Future Directions

In the previous section we reviewed four cognitive control domains that relate to action uncertainty, and showed how they share major research themes. Specifically, conflict adaptation, task switching, response inhibition and attentional control are context-specific, can operate in the absence of awareness, and are sensitive to reward. We propose that these findings suggest a shared notion of learning-based control. Here, task execution (or even mere instruction) results in the binding of active (task-relevant or -irrelevant) representations on the basis of contingency and reinforcement, including representations at the perceptual, motor, and goal levels. The resulting associative network enables contextually appropriate control across domains that address conceptually distinct challenges.

Besides clear integrative potential, an associative learning perspective on cognitive control also faces several challenges. Many are beyond the scope of the current paper, including the neural processes underlying goal representations and the extension of current ideas to areas such as working memory and reasoning. Here we focus on two more proximal challenges. First, we consider how generalization of cognitive control can derive from the specificity that characterizes associative learning. Second, we address how learning and cognitive control can be more broadly linked to each other in terms of purpose and computational implementation.

### Generalization

Associative learning is by definition restricted to learned processes or structures. This constraint fits nicely with the context-specific effects reviewed above. However, generalization has also been observed (for various examples, see the context-specificity sections of Tables A1 through A4), and this poses a challenge to the associative learning perspective. We discuss this issue for three cases of increasing challenge: Generalization to another item set, generalization to another task, and generalization from verbal instructions to behavioral implementation. Afterward, we briefly extend the issue of generalization to studies with a more applied focus.

**Item set.** Several studies demonstrated transfer of control from old to novel, or from manipulated to unmanipulated items. Crump and Milliken (2009) showed that a location-based CSPC effect generalizes to all items when only half of the items are actually CSPC-manipulated. Despite its intrinsic context-specificity, associative learning may still be well suited to account for this finding: Associations that are formed between location and

goal representations allow for transfer to any item that appears on the respective locations. Hence, generalization can be achieved by the overlap in features (e.g., location) between old and novel items as these can trigger appropriate control settings.

Which features provide the necessary overlap to enable transfer of learning-based control is not always clear. For the domain of response inhibition, for example, we already discussed that there is increased inhibition when a specific stop-signal repeats across two trials, but not when stop-signals are presented in different modalities (Bissett & Logan, 2012). However, these authors also demonstrated a learning-based enhancement of inhibition when the successive stop-signals were different but from the same modality. We speculate that the latter is attributable to the larger perceptual overlap for stop-signals within than between modalities, but it remains to be explored exactly where this overlap occurs. One simple possibility may be stop-signal location (i.e., anything presented after the go at the location of stop-signals triggers inhibition).

Generalization has also been observed for cases without clear feature overlap. Bugg and Chanani (2011) used a picture-word Stroop task in which some items were LWPC manipulated whereas other items (50% congruent) were not. A clear LWPC effect was observed even for the unmanipulated items, despite the fact that all items were presented centrally on the screen and location was thus not a salient feature to encode. Yet, all items consisted of animal names and pictures. Therefore, it is likely that the animal category was systematically coactivated at each item presentation (e.g., Levelt, Roelofs, & Meyer, 1999; see also Egner, 2014). The category representation, then, could become associated with attention modulation and allow LWPC transfer to all category members (even those not manipulated themselves). Because categories can be automatically extracted from item presentation (e.g., Ashby & Maddox, 2011; Goschke & Bolte, 2007), and categorization is rapid (e.g., Fabre-Thorpe, Delorme, Marlot, & Thorpe, 2001), rapid control via semantic categories is feasible.

In fact, Cañadas, Rodríguez-Bailón, Milliken, and Lupiáñez (2013) provided support for such a rapid, category-based modulation of goal representations. Three of four faces from one gender were associated with a high proportion of congruent flanker trials, whereas three of four faces of the other gender were associated with a low proportion of congruent trials. Interestingly, the fourth face within each gender was associated with the proportion congruency of the opposite gender group. A gender-specific proportion congruent effect was observed with larger interference for the gender group associated with a high proportion of congruent trials. Most importantly, the effect observed for the inconsistent faces was in the same direction as for the other exemplars of the same group, indicating that gender category had automatically been associated with the respective congruency proportions (Figure 1, arrow 5). Such category learning is expected if—together with exemplar specifics—the gender feature is automatically coactivated.

Hence, the associative learning perspective can account for generalization of control across item sets on the basis of *transfer*, occurring whenever (low-level) feature or (higher-level) category representations overlap between old and novel items. This provides an alternative to a classical supervisory control system—which runs the risk of reflecting operations of a homunculus

(Bugg, 2012; Bugg & Crump, 2012)—in accounting for domain-general observations.

**Distinct tasks.** Transfer across tasks can also occur via feature or category overlap. For example, Bugg, McDaniel, Scullin, and Braver (2011) showed that an LWPC manipulation in Stroop items affects reading colored neutral words from the same list. Moreover, an LWPC manipulation disrupted word processing on an unrelated secondary prospective memory task. This indicates that the LWPC manipulation affects word processing generally. Such generalization can be explained by associations between representations at the level of color processing and the inhibition of word reading. Consistently, context-specificity was demonstrated in a control experiment, where the prospective memory effect was not found for spatial information (Bugg et al., 2011; Experiment 2). Anderson, Laurent, and Yantis (2012) provided another example of transfer across tasks by single-feature overlap. Items of one specific color were systematically rewarded in a visual search task, resulting in increased capture by these items. Next, participants performed a flanker task and the flanker effect was largest when distractors were presented in the color that was previously rewarded in the visual search task. The association between a color feature and the goal to prioritize this information resulted in transfer of capture to another item set in a different task context.

Some studies observed dissociations in transfer between LWPC effects and CSEs. For example, Funes, Lupiàñez, and Humphreys (2010b) had participants responding to up- or down-pointing arrows by pressing left or right keys. These arrows were randomly presented either on a horizontal axis (left or right from fixation) or vertical axis (above or below fixation). The former resulted in Simon interference (i.e., interference between arrow and response locations), whereas the latter resulted in Spatial Stroop interference (i.e., interference between arrow location and arrow direction). A proportion congruency manipulation on the horizontal axis transferred to the (unmanipulated) vertical axis, but the CSE did not (cf. Torres-Quesada, Funes, & Lupiàñez, 2013; Wühr, Duthoo, & Notebaert, 2015). This dissociation has been interpreted in support of the existence of both a global supervisory control system (enabling proportion congruency transfer), and a transient, trial-by-trial control system that is context-specific. However, the associative learning perspective may provide a more parsimonious alternative. If the activation of one feature such as the manipulated axis causes small but consistent increases of activation across related features or dimensions (such as the unmanipulated axis), then the difference between the proportion congruency effect and the CSE may be explained as follows: Activation of the unmanipulated axis may have negligible impact on a trial-by-trial basis (i.e., no transfer at the congruency sequence level) but may still generate substantial impact because across larger time ranges small but consistent activations can result in learning (i.e., at the proportion congruency level).

A number of studies have reported transfer of control settings to distinct tasks that cannot be easily explained by feature overlap (Tables A1 through A4). Kan et al. (2013), for example, intermixed Stroop trials with simple sentence processing trials. Crucially, the sentences could be ambiguous (no conflict) or unambiguous (conflict). They observed a reduced Stroop congruency effect after ambiguous relative to unambiguous sentences. If conflict adaptation is context-specific, how can we incorporate such a finding? An answer to this question may be found in the conflict-

induced learning mechanism described above (Verguts & Notebaert, 2009). In Hebbian learning, all active representations and associations are bound. Hence, transfer of CSEs across tasks may depend on the extent to which they are simultaneously active (Braem et al., 2014). An absence of transfer is expected when task sets are used that substantially interfere with each other because such situation prompts a strategy in which only one task set is active at any time. However, when both tasks are either highly similar or sufficiently dissimilar, they can be simultaneously activated without much interference. The result would be a U-shaped relationship between task similarity and amount of transfer between tasks (for a more elaborate discussion, see Braem et al., 2014) as transfer occurs whenever tasks are either sufficiently similar or dissimilar to allow for concurrent maintenance. The study of Kan et al. (2013) may be a prime example of dissimilar tasks. This explanation is generally consistent with recent working memory models (Oberauer & Kliegl, 2006; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012) in which restrictions in working memory maintenance (i.e., capacity) are believed to arise from interference.

Finally, Karbach and Kray (2009) showed transfer of task-switching training to a structurally similar switching task (i.e., switch on every second trial) with different items and classification requirements in terms of a reduction of switch and mixing costs (cf. Karbach, Mang, & Kray, 2010). Yet, Pereg, Shahar, and Meiran (2013) showed that this transfer probably was not due to enhanced task switching ability but rather to specific working memory requirements, as transfer was not obtained based on training with structurally novel task switch designs (i.e., with random task order; cf. Shahar & Meiran, 2015). The latter absence of transfer is in line with an associative learning perspective as clear representational overlap is lacking to drive transfer. Interestingly, Karbach and Kray (2009) also observed transfer across control domains, from task switching to Stroop interference control—involving different perceptual, motor, and goal representations (cf. Karbach et al., 2010; but see Shahar & Meiran, 2015). Currently, such finding remains to be explained within the associative learning perspective. In general, determining the limits of transfer requires insight into the processing structures of the tasks as it is overlap in these structures that allows for transfer. Follow-up will be highly relevant for determining the reach of the currently formulated associative learning perspective.

In brief, the associative learning perspective postulates that transfer of control settings across tasks requires overlap between them. This requirement is fulfilled when perceptual or goal representations overlap, or when both tasks can be simultaneously maintained (i.e., overlap) in working memory (cf. Braem et al., 2014). Especially the latter is an interesting line for future research.

**From instructions to stimulus-response mapping.** An ambitious version of the associative learning perspective aims to provide an overarching framework for cognitive control. However, one major question arises: What drives behavioral and cognitive control before experience has provided the required associations between relevant representations? For example, how can subjects perform well above chance at the first stop-trial of a stop-signal task? This relates to what may be the most dramatic case of transfer in cognitive control, namely the transfer from instructions

to their implementation (Cole, Laurent, & Stocco, 2013; Liefooghe, Wenke, & De Houwer, 2012).

Recent computational work has focused on instruction-based learning (Doll, Jacobs, Sanfey, & Frank, 2009; Huang, Hazy, Herd, & O'Reilly, 2013; Ramamoorthy & Verguts, 2012). These models contain two complementary learning pathways (e.g., a slow-learning parietal pathway for habitual S-R mapping, and a fast-learning hippocampal pathway for the implementation of novel, arbitrary S-R translation). The slow-learning pathway can gradually conform its output to that of the fast-learning one *if* the environment is sufficiently systematic. Hence, cognitive control may build on brain areas that are continuously customized to the current goals and context as a result of fast learning, allowing them to gradually train slower learning mechanisms. Such interaction between fast- and slow-learning mechanisms allows for a balance between specificity and generalization, and more generally, for a cognitive agent that self-regulates his or her way through ever-changing environments.

Broadly, a learning-based continuum may be identified: Fast-learning systems allow for instruction-following, and drive increasingly slower learning systems that respectively implement context-based control, more automated forms of control, and eventually skills, habits, and cognitive reflexes that work independent of current goals. This is analogous to proposals for declarative memory (Alvarez & Squire, 1994; Cheng, 2013; Marr, 1971; O'Reilly & McClelland, 1994; Wickelgren, 1979) and procedural skill (Ashby, Turner, & Horvitz, 2010), where respectively hippocampus and basal ganglia are assumed to train cortical representations. An empirical prediction is that for novel tasks the precise instructions and the representations they activate will strongly determine the learning possibilities underlying context-driven cognitive control. This prediction remains to be tested, but the general notion that instructions enable (and restrict) learning has already received some support. Gaschler, Frensch, Cohen, and Wenke (2012), for example, showed how implicit learning of a fixed sequence of trials depends on the representational format of stimuli and responses in working memory as induced by instructions.

The link between instruction following and the associative learning perspective on cognitive control requires further scrutiny at conceptual and empirical levels. Future research should explore to what extent context, awareness, and reward are (necessarily) involved in the successful implementation of instructions, and how instructions regulate and modulate the development of successful cognitive control. The first efforts in this respect are starting to appear. Entel, Tzelgov, and Bereby-Meyer (2014) showed that the LWPC effect can be obtained by merely instructing the congruency level of an upcoming list. Moreover, Anderson and Folk (2014) showed that irrelevant flankers in the color of a no-go target inhibited specific target responses—even when S-R mappings were instructed anew on every trial. This indicates that instruction-based learning was sufficiently strong for features to trigger inhibition (cf. Wokke, Van Gaal, Scholte, Ridderinkhof, & Lamme, 2011). Such observations may form the basis for conceptualizing instructions as cognitive control.

**Beyond basic paradigms.** Training improves performance in most domains, and this is no different for cognitive control. For example, both task switching (reduced switch costs with practice) and response inhibition (reduced stopping time with practice)

benefit from training (e.g., Thorell et al., 2009; Spierer, Chavan, & Manuel, 2013). What remains undetermined is the theoretically and practically more relevant issue of generalization (i.e., transfer) of control functions beyond basic paradigms of experimental psychology. The associative learning prediction is clear: Transfer occurs to the extent that two tasks overlap. Without aiming for a comprehensive review, we here discuss some relevant work in this area.

Videogame training (i.e., not specifically targeting any control function) may benefit task switching ability, but results are not unequivocal. Green, Sugarman, Medford, Klobusicky, and Bavelier (2012) and Strobach, Frensch, and Schubert (2012) observed a positive impact of videogame training on a predictable alternate-runs task switch design. Instead, Boot, Kramer, Simons, Fabiani, and Gratton (2008) found no effect on a random task switching paradigm. As far as we know, the impact of training with video games has not been explored extensively for conflict adaptation, response inhibition or attentional control—at least for the paradigms and effects discussed here. However, for response inhibition there is tentative support that no positive impact is to be expected, as Colzato, van den Wildenberg, Zmigrod, and Hommel (2013) found no improved response inhibition for gamers versus nongamers on a stop-signal task. More generally, in a recent review Oei and Patterson (2014) concluded that training of videogames only transfers to specific perceptual or cognitive tasks when there are common demands, in line with the associative learning perspective. As using videogames for cognitive enhancement is a promising field of research (Anguera et al., 2013), the associative learning perspective may provide a framework from which to guide future efforts.

Training and transfer of control may have large potential for the treatment of disorders that relate to (temporary or long-lasting) lapses of control, such as substance abuse, eating disorders, and pathological gambling. Recent work has started to explore this potential. For example, besides well-known S-S conditioning in this domain (e.g., Veling, Aarts, & Stroebe, 2011), cognitive control functions themselves can be subject to conditioning. Based on the work showing that response inhibition can be triggered by items associated with stop- or no-go-trials (e.g., Verbruggen & Logan, 2008), it has been explored if (motor) impulses and desires that cause eating disorders may benefit from contextually driven inhibition. Houben and Jansen (2011) showed that using chocolate-related no-go items decreased subsequent chocolate consumption relative to conditions where such items indicated going. Similarly, Houben (2011) trained participant with a stop-signal task. Participants with low baseline inhibitory control reduced food intake for one high-calorie item that was systematically paired with stop-signals relative to another high-calorie item that was not systematically paired (for a similar finding on alcohol inhibition, see Jones & Field, 2013). Interestingly, the study of Houben (2011) thus shows item-specific effects.

Other studies seem to pose a challenge to the associative learning perspective as currently formulated. For example, Verbruggen, Stevens, and Chambers (2014) showed that combining stop-signal and gambling tasks (dual task design) resulted in more conservative betting strategies (i.e., lower bets with a higher probability of winning). Moreover, a short period of inhibitory training resulted in more conservative betting strategies in gambling with a delay of two hours. The authors interpreted their results as a 'transfer of

cautiousness,' which is challenging to understand within the associative learning perspective because transfer of a 'controlled strategy' is observed in the absence of clear representational overlap between tasks. A similar issue holds for the study by Spierer et al. (2013), who concluded that training can boost inhibition in the absence of clear item-goal contingencies.

In conclusion, training of control functions is robust, but transfer across tasks requires further exploration. Whereas previous work on the issue of transfer was largely data-driven, the associative learning perspective on cognitive control may offer a framework from which to address this issue systematically across different domains and groups (e.g., children at early age; Perone, Molitor, Buss, Spencer, & Samuelson, 2015). Although it can be hard to determine a priori the extent of representational overlap, and thus whether or not transfer can be expected, the associative learning perspective postulates that the degree of transfer should vary as a function of representational overlap.

## Computational Integration

The previous sections strongly motivate further exploration of associative learning as the mechanism underlying cognitive control. Along this way, a clear challenge will be to integrate learning and control with respect to their overall purpose and implementation.

**The purpose of learning and control.** The purpose of learning is performance optimization, and we propose that the same is true for cognitive control (Botvinick & Cohen, 2014; Cohen, McClure, & Yu, 2007; Egner, 2014). For example, conflict adaptation may not occur specifically to overcome conflict in information processing but rather serve the more general purpose of performance optimization. A recent study supports this notion. Verguts, Vassena, and Silvetti (2015) presented a computational model in which effort exertion is adaptively learned by considering rewards, costs, and task difficulty. An important feature for current purposes is that this model—which aims to optimize the investment of effort—indirectly generates proportion congruency and congruency sequence effects (although conflict management is not the model's target). Reversely, a model targeting conflict management (Verguts & Notebaert, 2008) indirectly optimizes performance levels (see simulations in Appendix B). Such a bidirectional link suggests that learning how to optimize performance may be the core principle underlying cognitive control. Empirical efforts should follow up on this.

**Implementing learning and control.** Online adjustments using deviations between predicted and obtained values (i.e., prediction error or PE) drive learning and parameter estimation, and these are required to optimize performance (Alexander & Brown, 2011; Friston, 2010; Rao & Ballard, 1999; Rescorla & Wagner, 1972; Silvetti, Seurinck, & Verguts, 2011; Verguts et al., 2015). Importantly, the notion that PEs drive learning has recently received renewed empirical interest and direct support. For example, mimicking reward PE by optogenetic activation of rodent dopamine neurons results in cue-reward learning (Steinberg et al., 2013). In humans, PEs drive pharmacologically induced amnesia for learned fear (Sevenster, Beckers, & Kindt, 2013). Hence, PE may be an important empirical signature to look for when investigating performance optimization in cognitive control. One avenue to test this would be to focus on the well-known finding that

unsurprising events (i.e., lack of PE) are blocked from learning, a phenomenon referred to as blocking (Kamin, 1969). Does blocking occur in cognitive control? For example, will context-specific proportion congruency learning for one cue block learning for a second cue that predicts control demands with equal probability? This is currently unknown, but the exploration of analogs in cognitive control of well-known learning phenomena will ultimately decide on the true potential of the associative learning perspective.

Predictions and PEs can occur on different levels of information processing. For example, Den Ouden, Kok, and De Lange (2012) distinguished between PEs on the levels of perceptual, cognitive, and reward processing. Without disputing the other two, we believe that mismatches between expected and actual reward outcomes (i.e., reward Pes) are especially important for cognitive control. First, the current review demonstrates the systematic modulation of cognitive control functions by reward. This modulation may critically depend on performance contingency. For example, Braem et al. (2012) rewarded a small proportion of correct responses (and no incorrect responses), and observed more conflict adaptation after rewarded as compared to nonrewarded correct trials (see also Stürmer et al., 2011). Interestingly, their reward trials were actually reward PE trials, as reward trials were randomly selected and far less frequent than nonreward trials. In contrast, Soutschek et al. (2014) provided rewards systematically as a function of a fixed performance threshold, and no reward-based modulation of conflict was observed—as if performance alone allowed for accurate reward prediction without PE. Together, these studies suggest that reward PE dominates adaptation. Importantly, and especially in the absence of external reward signals, intrinsic reward PEs based on performance outcome might have a currently underestimated role in driving adaptations. For example, it has been hypothesized that correctly solving an incongruent trial could be intrinsically rewarding (Braem et al., 2012; Braem, Coenen, Bombeke, van Bochove, & Notebaert, 2015; Schouppe et al., 2015). Similarly, recent attentional capture (Chetverikov, Jóhannesson, & Kristjánsson, 2015) and response inhibition (Aarts, De Houwer, & Pourtois, 2012) studies demonstrated that correct versus incorrect visual search or inhibition performance was intrinsically evaluated as positive. Future studies should explore the potentially critical role of intrinsic reward PE in driving cognitive control.

A second argument for reward PEs as a driving force in cognitive control concerns the neural overlap between learning, reward PE and cognitive control processes, sharing among others the basal ganglia and anterior cingulate cortex (Alexander & Brown, 2011; Silvetti, Seurinck, & Verguts, 2011; Silvetti, Alexander, Verguts, & Brown, 2014). Although beyond the scope of the current review, we briefly note that the associative learning perspective predicts such overlap. Intriguingly, rodent studies show that reward PE on the current trial leads anterior cingulate cortex to signal the need for enhanced neural resources (i.e., enhanced attention) on subsequent trials (Bryden, Johnson, Tobia, Kashtelyan, & Roesch, 2011). It would be very interesting to see the outcomes of similar studies in human participants.

In general, exploring the computational foundation of learning and control may offer a way around the potential circularity that accompanies the concept of context (i.e., the context can be said to have overlapped whenever transfer of control is present) by pro-

viding testable predictions that can potentially falsify the associative learning perspective. One example may be the prediction that a reward PE generates similar adaptation as does conflict.

## Conclusions & Outlook

Owing to a long and rich tradition, cognitive control has become a central concept in cognitive science that comprises a heterogeneous set of functions. These functions are studied in relatively independent research domains that each have their own specialized paradigms and domain-specific theories. Over the last decade, various cognitive control domains related to the resolution of action uncertainty have concurrently welcomed a large number of studies exploring the roles of context, reward and awareness. Here we reviewed these themes, and inspired by the review we proposed a perspective in which control derives from associations between perceptual, motor, and goal representations. This associative learning perspective holds three major theoretical contributions.

First and most importantly, the perspective offers broad integration across the heterogeneous landscape of cognitive control research and theory. Our review shows how typical control phenomena are context-specific, operate in the absence of awareness, and are sensitive to reward; and as each of these themes can be envisaged as a core characteristic of learning they provide an empirical foundation for the notion that cognitive control is grounded in associative learning. Indeed, we have shown this to be the case for a wide range of cognitive control functions including conflict adaptation, task switching, response inhibition and attentional control. Whereas these functions are typically assumed to address conceptually distinct challenges, we here converged these functions onto a single learning principle that is biologically plausible and computationally grounded. Importantly, as we have seen above, an associative learning perspective accommodates rather than rejects various domain-specific theories, and provides simplification with respect to several conceptual dichotomies (for specific examples, see Table 2).

Second, the mapping of cognitive control to associative learning inspires further cross-fertilization between these two research fields. The role of cognitive control in learning is interesting (e.g., Beckers, Miller, De Houwer, & Urushihara, 2006; Blaisdell, Sawa, Leising, & Waldmann, 2006), but the reverse is especially relevant for current purposes. The systematic exploration of transfer (i.e., generalization) in cognitive control as discussed above is a first step, but typical learning phenomena such as blocking and overshadowing (i.e., reduced learning for a cue in the presence of a stronger, more salient cue) remain to be tested. The associative learning perspective predicts to find analogs of these effects in cognitive control tasks. Further cross-fertilization is prompted between the four cognitive control domains discussed here. Specifically, extensive exploration of cross-domain interactions such as the conflict-modulated task-switch cost discussed above will be very valuable; the associative learning perspective predicts and frames this type of observation.

Third, the associative learning and contextual priming processes that are at the basis of the here-defended perspective provide a *self-regulating* mechanism that allows banishing the homunculus from our conceptual frameworks on cognitive control. The cognitive agent learns the relevant cues that determine control demands, and control settings can then be contextually triggered. Critically,

although being intrinsically context-specific, associative learning still allows for substantial generalization due to representational overlap. This overlap may take several forms, ranging from overlap at the item level (e.g., item features, item categories, otherwise semantically related features) to the simultaneous and active maintenance of task sets (e.g., overlap in working memory). Hence, the notion that cognitive control is self-regulated through associative learning does not refute its use across broader settings.

In a nutshell, rather than being mere ballast from earlier trials, *learning fast and slow* grounds cognitive control. This perspective provides a solid theoretical framework that integrates past research efforts, but also generates clear novel predictions and concrete challenges for future research. Examples of these are provided in the sections above. Importantly, although at the basis of high-impact computational work, associative learning is often neglected in the interpretation and framing of new observations across cognitive control research, and we hope that the current paper inspires further efforts in this direction. Ultimately, an ambitious version of the perspective aims to understand goal-directed behavior in its broadest sense. This will require extending its reach in various ways. On the one hand, we did not discuss the exact mechanisms that underlie the implementation of learning-based control. Eventually, we need to link the associative learning perspective to current and specified models of these processes. On the other hand, efforts should go beyond the four selected cognitive control domains of the current paper, and extend to areas such as working memory and reasoning, where challenges may be even bigger because of the abstract nature of the involved representations. A full understanding of learning-based control will require addressing these challenges.

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(*Appendices follow*)

## Appendix A

### Literature Searches

Search results for the domains of conflict adaptation (Table A1), task switching (Table A2), response inhibition (Table A3), and attentional control (Table A4). We briefly describe the relevant finding and interpret whether or not it is in line with context-specificity, operation in the absence of awareness, or reward-

sensitivity (indexed by "yes" or "no"; "unclear" indicates that the study is relevant, but currently the associative learning perspective is too little specified to make a firm claim with respect to confirmation). Footnotes below each table provide the strings that we used to initiate the Web of Science literature search.

Table A1
*Conflict Adaptation (i.e., Congruency Sequence and Proportion Congruency Effects)*

| Reference | Task(S) | Effect (context) | Finding | Confirmation |
|---|---|---|---|---|
| Context-specificity[a] | | | | |
| Abrahamse et al. (2013) | Stroop | ISPC | ISPC effect occurs in the absence of item-response contingencies | yes |
| Akçay & Hazeltine (2008) | Simon | CSE | CSE within but not across segregated item sets assigned to two separate response sets. CSE across task sets when either item or response sets overlapped | yes |
| Akçay & Hazeltine (2011) | Simon + flanker | CSE | CSE within but not across conflict types | yes |
| Atalay & Misirlisoy (2012) | Stroop | ISPC | ISPC effect was observed both within and between languages | yes |
| Atalay & Misirlisoy (2014) | Stroop | ISPC | ISPC effect | yes |
| Braem et al. (2011) | Simon | CSE | CSE across response sets when similar, but not when distinctive (i.e., hands versus feet) | yes |
| Braem et al. (2014) | Flanker | CSE | CSE when previous and current task-irrelevant color surrounding the flanker item was the same | yes |
| Bugg & Chanani (2011) | Stroop | LWPC | Transfer of LWPC to PC-unmanipulated items | no |
| Bugg et al. (2008) | Stroop | ISPC | Contextual control can work across multiple levels | yes |
| Bugg, Jacoby, &Chanani (2011) | Stroop | LWPC | Transfer of LWPC to PC-unmanipulated items | no |
| Bugg, McDaniel, et al. (2011) | Stroop | ISPC | ISPC effect that transfers to PC-unmanipulated items | yes/no |
| Bugg & Hutchison (2013) | Stroop | ISPC | Item-specific control depends on item-response contingencies in the design, and can transfer to novel items | yes |
| Cañadas et al. (2013) | Flanker | CPSC (gender) | CSPC effect that generalizes to novel items | yes/no |
| Cho et al. (2009) | Stimulus response compatibility task | CSE | CSE across horizontal and vertical dimensions | no |
| Crump et al. (2006) | Stroop | CSPC (shape/ location) | First demonstration of the CSPC effect | yes |
| Crump et al. (2008) | Stroop | CSPC (location/ shape) | CSPC effect depends on attention for context cue as well as on the relative salience of target, distractor, and context dimensions | yes |
| Crump et al. (2009) | Stroop | CSPC (location) | CSPC effect that transfers to PC-unmanipulated items | yes/no |
| D'Angelo et al. (2013) | Sequence learning | CSE | CSE within but not across conflict types | yes |
| Egner et al. (2007) | Stroop + Simon | CSE | CSE within but not across conflict types | yes |
| Fernandez-Duque & Knight (2008) | Number Stroop + flanker/Number Stroop + Color Stroop | CSE | CSE was observed across conflict types | no |
| Fischer et al. (2010) | Simon | CSE | CSE independent of task load, within but not across (single versus dual) task contexts | yes |
| Fischer et al. (2014) | Dual-task Paradigm | CSPC (location) | Between task interference can be reduced by cues indicating the PC-manipulated location but not cues that indicate the interference level | yes |

(*Appendices continue*)

Table A1 (*continued*)

| Reference | Task(S) | Effect (context) | Finding | Confirmation |
|---|---|---|---|---|
| Forster & Cho (2014) | Simon + Stroop | CSE | CSE within but not across conflict types | yes |
| Freitas et al. (2007) | Flanker (Exp. 1)/flanker + color Stroop (Exp. 2)/flanker + spatial Stroop (Exp. 3) | CSE | CSE across horizontal and vertical dimensions (Exp. 1) and across conflict types (Exp. 2–3) | no |
| Freitas & Clark (2015; Exp. 1–3) | Stroop-trajectory (Exp. 1)/Spatial Stroop + flanker (Exp. 2)/Stroop-trajectory + flanker (Exp. 3) | CSE | CSE across horizontal and vertical dimensions (Exp. 1) and across conflict types (Exp. 2–3) | no |
| Freitas & Clark (2015; Exp. 3) | Stroop-trajectory + Simon | CSE | No CSE across conflict types (Exp. 3) | yes |
| Funes et al. (2010a; Exp 1–2) | Spatial Stroop + flanker/spatial Stroop + Simon | CSE | CSE within but not across conflict types | yes |
| Funes et al. (2010a; Exp. 3 and 4) | Spatial Stroop | CSE | CSE across horizontal and vertical dimensions | no |
| Funes et al. (2010b; Exp. 1) | Spatial Stroop + Simon | CSE | CSE within but not across conflict types | yes |
| Funes et al. (2010b; Exp. 2) | Spatial Stroop + Simon | LWPC | Transfer of LWPC between conflict types | no |
| Hazeltine et al. (2011; Exp. 1, 4) | Prime-target | CSE | CSE within but not between item modality, unless two item sets were used | yes |
| Hazeltine et al. (2011; Exp. 2, 3) | Prime-target | CSE | CSE across item set when both assigned to the same, but not to different response set | yes |
| Hazeltine & Mordkoff (2014) | Stroop | ISPC | No evidence for item-specific triggering of control representations in the observed ISPC effect | no |
| Heinemann et al. (2009; Exp. 1) | Prime-target | CSPC (color) | CSPC effect | yes |
| Kan et al. (2013) | Stroop + sentence processing (Exp. 1)/Stroop + perceptual ambiguity (Exp. 2) | CSE | CSE across conflict types | no |
| Kiesel et al. (2006) | Parity/magnitude task | CSE | CSE for task repetition but not alternation | yes |
| Kim & Cho (2014) | Flanker | CSE | CSE across fingers when assigned to one hand, but not when assigned to two hands | yes |
| King et al. (2012) | Flanker | CSPC (location) | CSPC effects may reflect response caution triggered by contextually surprising items rather than contextually cued attention modulation | yes |
| King et al. (2012) | Flanker | CSPC (location) | CSPC effect | yes |
| Kleiman et al. (2014) | letter flanker + gender flanker (Exp. 1)/letter flanker + race sequential priming (Exp. 2) | CSE | CSE across conflict types | no |
| Kunde & Wühr (2006; Exp. 1) | Prime-target | CSE | CSE across horizontal and vertical dimensions | no |
| Kunde & Wühr (2006; Exp. 2) | Simon + prime-target | CSE | CSE across conflict types, but smaller than within conflict type | no/yes |
| Kunde et al. (2012) | Simon + affective Interference | CSE | CSE within but not across conflict types | yes |
| Lee & Cho (2013; Exp. 1A, 1B, 4) | Simon or Spatial Stroop | CSE | No CSE across but only within horizontal and vertical dimensions | yes |
| Lee & Cho (2013; Exp. 2, 3) | Simon + Spatial Stroop | CSE | CSE across conflict types when the same, but not when different response sets were used for both tasks | yes |
| Notebaert & Verguts (2008) | Simon + SNARC | CSE | CSE across conflict type, but only when task relevant information was the same | yes |
| Panadero et al. (2015) | Stroop | CSPC (mask identity) | CSPC effect | yes |
| Reuss et al. (2014) | Prime-target | CSPC (prime or target format) | CSPC effect | yes |
| Rünger et al. (2010) | Flanker + number Stroop | CSE | CSE was not observed across tasks | yes |
| Schlaghecken et al. (2011) | Simon + prime-target | CSE | CSE within but not across conflict types | yes |
| Schmidt & Weissman (2014) | Prime-target | CSE | CSE across horizontal and vertical dimensions | no |

(*Appendices continue*)

Table A1 (*continued*)

| Reference | Task(S) | Effect (context) | Finding | Confirmation |
|-----------|---------|------------------|---------|--------------|
| Schmidt & Besner (2008) | Stroop | ISPC | No evidence for item-specific triggering of control representations in the observed ISPC effect | no |
| Schmidt (2013) | Stroop | ISPC | No evidence for item-specific triggering of control representations in the observed ISPC effect | no |
| Schouppe, Demanet, et al. (2014) | Flanker | CSPC (location) | CSPC effect | yes |
| Schouppe, de Ferrerre, et al. (2014) | Prime-target | CSPC (location) | CSPC effect | yes |
| Schouppe, Ridderinkhof, et al. (2014) | Stroop | CSPC (shape) | CSPC effect | yes |
| Shedden et al. (2013; Exp. 1) | Global-local task | ISPC | ISPC effect | yes |
| Shedden et al. (2013; Exp. 2) | Stroop | ISPC | ISPC effect | yes |
| Spapé & Hommel (2008) | Stroop | CSE | CSE within but not between contexts (voice gender) | yes |
| Spapé et al. (2015) | Simon | CSE | CSE was disrupted by a change in task-irrelevant avatar identity, but only when avatar was static | yes/no |
| Verbruggen et al. (2005) | Spatial Stroop + Simon | CSE | CSE within but not across conflict types | yes |
| Vietze & Wendt, (2009) | Flanker | CSPC (color) | Item color can drive CSPC effect | yes |
| Wendt et al. (2006) | Simon + flanker or Stroop | CSE | CSE within but not across conflict types | yes |
| Wendt et al. (2008) | Flanker | CSPC (location) | CSPC occurred when employing four PC-manipulated locations | yes |
| Wendt & Kiesel (2011) | Flanker | CSPC (foreperiod) | Foreperiod can serve as a contextual cue in CSPC effect | yes |
| Wühr et al. (2015; Exp. 1, 2) | Simon | CSE | CSE within horizontal and vertical dimensions, yet only across dimensions when both tasks shared the relevant dimension | yes |
| Wühr et al. (2015; Exp. 3) | Simon + Stroop | CSE | CSE within but not across conflict types | yes |
| Operation in the absence of awareness[b] | | | | |
| Ansorge et al. (2011) | Prime-target | CSE | No CSE in the absence of prime awareness | no |
| Atalay & Misirlisoy (2014) | Stroop | ISPC | ISPC effect independent of awareness of PC manipulations | yes |
| Blais et al. (2012) | Stroop | PC | PC effect develops without awareness of the specific proportion congruency | yes |
| Bodner & Mulji (2010) | Prime-target | LWPC | LWPC effect without awareness of the specific PC | yes |
| Crump et al. (2008) | Stroop | CSPC | CSPC effect does not depend on awareness of the PC manipulation | yes |
| D'Angelo et al. (2013) | Sequence learning | CSE | CSE within conflict type without awareness of the source of conflict | yes |
| Desender et al. (2013) | Prime-target | CSE | CSE in the absence of prime awareness | yes |
| Desender et al. (2014) | Prime-target | CSE | CSE only after trials on which participants reported to have experienced response conflict | no |
| Francken et al. (2011) | Prime-target | CSE | CSE in the absence of prime awareness | yes |
| Hasegawa & Takahashi (2014) | Prime-target | LWPC/CSE | LWPC effect and CSE (on errors) in the absence of prime awareness | yes |
| Heinemann et al. (2009; Exp. 2) | Prime-target | CSPC (color) | CSPC effect absent when unaware of the task-irrelevant dimension | no |
| Jiang et al. (2013) | Prime-target | LWPC | LWPC effect when unaware of the prime and its congruency with target | yes |
| Jiménez et al. (2009) | Sequence learning | CSE | CSE is present when unaware of the source of incongruency | yes |
| Panadero et al. (2015) | Stroop | CSPC (mask identity) | CSPC effect without awareness of the task-irrelevant dimension | yes |
| Reuss et al. (2014) | Prime-target | CSPC (prime or target format) | CSPC effect without awareness of both context and task-irrelevant dimension | yes |
| Schouppe, de Ferrerre, et al. (2014) | Prime-target | CSPC (location) | CSPC effect is not modulated by awareness | yes |
| Van Gaal et al. (2010) | Prime-target | CSE | CSE in the absence of prime awareness | yes |

(*Appendices continue*)

Table A1 (*continued*)

| Reference | Task(S) | Effect (context) | Finding | Confirmation |
|---|---|---|---|---|
| Reward-sensitivity[c] | | | | |
| Braem et al. (2012; Exp. 1) | Flanker | CSE | Enhanced CSE following performance-contingent reward signals | yes |
| Braem et al. (2014) | Flanker | CSE | Enhanced CSE following performance-contingent reward signals when irrelevant visual context (surrounding shape color) repeated, but not when it alternated | yes |
| Stürmer et al. (2011) | Simon | CSE | Enhanced CSE following performance-contingent reward signals | yes |
| Van Steenbergen et al. (2012) | Flanker | CSE | CSE diminished following non-contingent reward signals | unclear |
| Van Steenbergen et al. (2012) | Flanker | CSE | CSE diminished following non-contingent reward signals | unclear |

*Note.* CSE = congruency sequence effect; PC = proportion congruency; CSPC = context-specific proportion congruency; LWPC = list-wide proportion congruency; ISPC = item-specific proportion congruency.
[a] Web of Science advanced search string: "*TS=(("congruen* sequence" OR "sequen* congruen*" OR "conflict adaptation effect" OR Gratton OR "proportion congruen*") AND (context* OR transfer* OR specific* OR context-specific*)) AND SU=(Psychology OR Neurosciences & Neurology OR Behavioral Sciences) AND PY=(2005–2015).*"   [b] Web of Science advanced search string: "*TS=(("congruen* sequence" OR "sequen* congruen*" OR "conflict adaptation effect" OR Gratton OR "proportion congruen*") AND (aware* OR conscious* OR implicit OR unconscious*)) AND SU=(Psychology OR Neurosciences & Neurology OR Behavioral Sciences) AND PY=(2005–2015).*"   [c] Web of Science advanced search string: "*TS=(("congruen* sequence" OR "sequen* congruen*" OR "conflict adaptation effect" OR Gratton OR "proportion congruen*") AND reward*) AND SU=(Psychology OR Neurosciences OR Behavioral Sciences) AND PY=(2005–2015).*"

Table A2

*Task Switching (i.e., Switch Costs and Task Priming Effects)*

| Reference | Tasks | Switching | Finding | Confirmation |
|---|---|---|---|---|
| Context-specificity[a] | | | | |
| Crump & Logan (2010) | Magnitude-Parity | Cued | Location-specific switch-proportion manipulation modulated the switch cost | yes |
| Denkinger & Koutstaal (2009; Exp. 2) | Five different classification tasks | Cued | Priming effects increased with number of repetitions especially when the task context was constant | yes |
| Denkinger & Koutstaal (2009; Exp. 2) | Five different classification tasks | Cued | Repetition-related facilitation was preserved even when the task context changed | unclear |
| Farooqui & Manly (2015) | Size-magnitude; letter-case; | Cued | Cues that predict task switches facilitate switching | yes |
| Forrest et al. (2014) | Parity-magnitude | Cued | Switch cost increases when stimulus set is changed while tasks remain the same | unclear |
| Gade & Koch (2007) | Letter-parity | Cued | Cue–task associations are formed and the implementation of new cue–task mappings can be hampered by previously learnt associations | yes |
| Leboe et al. (2008) | Habitat-size | Cued | Location-specific switch-proportion manipulation modulated the switch cost | yes |
| Karbach & Kray (2009) | Ten different classification tasks | AABB | Switch costs reduction by training transferred to different tasks (different stimuli, same responses) | no |
| Karbach et al. (2010) | Letter-parity; magnitude-position | AABB | Switch costs reduction by training transferred to different tasks (different stimuli, same responses) | no |
| Kieffaber et al. (2013) | Comparison-identity | Cued | Task switches requiring the reconfiguration of stimulus-set alone incurred smaller residual switch costs than task switches requiring reconfiguration of both stimulus- and response-set | unclear |

(*Appendices continue*)

Table A2 (*continued*)

| Reference | Tasks | Switching | Finding | Confirmation |
|---|---|---|---|---|
| Manly et al. (2014) | Four different same/different judgment tasks | Cued | Primes can trigger specific control settings that transfer across different phonological-semantic same/different judgments task | no |
| Mayr & Bryck (2007) | Orientation-color | Cued | Stimulus/response locations predictive of task set eliminated the error switch cost | yes |
| Minear & Shah (2008) | Eight different classification tasks | AABB and/or cued | Switch costs reduce with training but no transfer is obtained to a different set of S-R rules | yes |
| Shahar & Meiran (2015) | Six different classification tasks | Cued | No reliable impact of training on switch cost in a design with different tasks | yes |
| Pereg et al. (2013) | Various different classification tasks | AABB/AAABBB/ cued | Switch costs reduction by training did not transfer to different task switching designs (different stimuli, same responses, different task sequences) | yes |
| Prior & Gollan (2013) | Language switching; color-shape switching | Cued | No transfer between the two tasks with respect to switch costs | yes |
| Rubin & Koch (2006) | Horizontal-vertical | Cued | Task-irrelevant color feature reduced switch cost when predictive of task set (but only with short cue-target interval) | yes |
| **Operation in the absence of awareness**[b] | | | | |
| Crump & Logan (2010) | Magnitude-parity | Cued | Location-specific switch-proportion manipulation modulated the switch cost in absence of awareness of the context manipulation | yes |
| Farooqui & Manly (2015) | Size-magnitude; letter-case; | Cued | Cues that predict task switches facilitate switching when subliminally presented | yes |
| Lau & Passingham (2007) | Phonological-Semantic | Cued | Unconsciously perceived primes indicating the alternative task impaired performance on the current task | yes |
| Manly et al. (2014) | Four different same/different judgment tasks | Cued | Not consciously perceived primes can trigger specific control settings | yes |
| Reuss et al. (2011; Exp. 1) | Magnitude-parity | Voluntary | Masked cues steer voluntary task choices | yes |
| Reuss et al. (2011; Exp. 2) | Magnitude-parity | Voluntary | Masked cues associated with either task repetition or task switch steer voluntary task choices | yes |
| Weibel et al. (2013) | Phonological-semantic | Cued | Unconsciously perceived primes indicating the alternative task impaired performance on the current task | yes |
| Zhou & Davis (2012a) | Phonological-semantic | Cued | Unconsciously perceived primes can trigger specific task sets to which they were associated previously | yes |
| Zhou & Davis (2012b) | Phonological-semantic | Cued | Unconsciously perceived primes can trigger specific task sets to which they were associated previously | yes |
| **Reward-sensitivity**[c] | | | | |
| Braem et al. (2012; Exp. 2) | Flanker-Simon | Univalent items | The CM-TSC was larger following performance-contingent reward | yes |
| Braem et al. (2013) | Parity-Magnitude | Cued | The CM-TSC was smaller following performance-contingent reward in the form of positive pictures, but larger following non-contingent reward in the form of positive pictures (versus negative pictures) | yes/unclear |
| Umemoto & Holroyd (2015) | Alphabet-magnitude | Cued | Switch costs are enhanced when the previous trial is rewarded | yes |

*Note.* AABB indicates switching of task on every second trial, et cetera.
[a] Web of Science advanced search string: "*TS=(("task prim\*" OR "task cue\*" OR "switch\* cost" OR "task set") AND switching AND (context\* OR transfer\* OR specific\* OR context-specific\*)) AND SU=(Psychology OR Neurosciences & Neurology OR Behavioral Sciences) AND PY=(2005–2015)*". [b] Web of Science advanced search string: "*TS=(("task prim\*" OR "task cue\*" OR "switch\* cost" OR "task set") AND switching AND (aware\* OR conscious\* OR implicit OR unconscious\*)) AND SU=(Psychology OR Neurosciences & Neurology OR Behavioral Sciences) AND PY=(2005–2015)*". [c] Web of Science advanced search string: "*TS=(("task prim\*" OR "task cue\*" OR "switch\* cost" OR "task set") AND switching AND reward\*) AND SU=(Psychology OR Neurosciences & Neurology OR Behavioral Sciences) AND PY=(2005–2015).*"

Table A3

*Response Inhibition (i.e., Stop-Signal and Go/No-Go Performance)*

| Reference | Task(s) | Finding | Confirmation |
|---|---|---|---|
| **Context-specificity[a]** | | | |
| Anderson & Folk (2012) | Go/no-go | Presenting irrelevant flankers in the color of a no-go target inhibits specific target responses | yes |
| Anderson & Folk (2014) | Go/no-go | Presenting irrelevant flankers in the color of a no-go target inhibits specific target responses, even when stimulus-response mappings change with every trial | no |
| Bissett & Logan (2012) | Stop-signal | Response inhibition performance enhanced at second of two consecutive stop trials with same (Exp. 1) or different but shared modality stop-signals (Exp. 2–4), but not with stop-signals from different modalities (Exp. 5–6) | yes/no |
| Chiu & Aron (2014) | Go/no-go | No-go item primed slowing only when the task context included stopping | yes |
| Enge et al. (2014) | Stop-signal or go/no-go | No transfer from stop-signal and go/no-go training to Stroop task performance | yes |
| Feldman et al. (2015) | Go/no-go | A no-go item on previous trial increased performance on current trial only when the same go/no-go rule was applied | yes |
| Giesen & Rothermund (2014) | Stop-signal | Irrelevant item features can become associated with response inhibition | yes |
| Wokke et al. (2011) | Go/no-go | Item associated with a no-go trial slows performance, even when the go and no-go associations change on a trial-by-trial basis | no |
| **Operation in the absence of awareness[b]** | | | |
| Chiu & Aron (2014) | Go/no-go | Subliminal no-go item primed slowing only when the task context included stopping | yes |
| Hepler et al. (2013) | Go/no-go | Subliminal action/inaction concepts prime response inhibition | yes |
| Hughes et al. (2009) | Go/no-go | Subliminal no-go item primed slowing | yes |
| Lin & Murray (2015) | Go/no-go | Slowed responding after a masked no-go item | yes |
| Parkinson & Haggard (2014) | Go/no-go | Unconsciously perceived items bias 'free' choice behavior (i.e., act or inhibit) based on their go or no-go associations | yes |
| Van Gaal et al. (2008) | Go/no-go | Slowed responding to go items when primed with a subliminal no-go item | yes |
| Van Gaal et al. (2009) | Stop-signal | Slowed responding with subliminal stop-signals | yes |
| Van Gaal et al. (2010) | Go/no-go | Slowed responding with a subliminal no-go item | yes |
| Van Gaal et al. (2011) | Stop-signal | Slowed responding with subliminal stop-signals | yes |
| Verbruggen, Best, et al. (2014) | Stop-signal | Items that were earlier systematically presented in stop-trials were responded to slower when now presented in a go-trial | yes |
| Verbruggen & Logan (2008) | Go/no-go | After training, switching the go and no-go items slowed responding | yes |
| Wokke et al. (2011) | Go/no-go | Not consciously perceived items associated with a no-go trial slow performance, even when the go and no-go associations change on a trial-by-trial basis | yes |
| **Reward-sensitivity[c]** | | | |
| Boehler et al. (2012) | Stop-signal | The SSRT was smaller for rewarded versus unrewarded stop signals | yes |
| Boehler et al. (2014) | Stop-signal | The SSRT was smaller for rewarded versus unrewarded stop signals | yes |

*Note.* SSRT = stop-signal reaction time.
[a] Web of Science advanced search string: "*TS=(("go/no-go" OR "go-nogo" OR"stop-signal" OR "stop signal" OR (go AND "no-go") OR (go AND nogo)) AND (context\* OR transfer\* OR specific\* OR context-specific\*) AND inhibition) AND SU=(Psychology OR Neurosciences & Neurology OR Behavioral Sciences) AND PY=(2005–2015).*" [b] Web of Science advanced search string: "*TS=(("go/no-go" OR "go-nogo" OR"stop-signal" OR "stop signal" OR (go AND "no-go") OR (go AND nogo)) AND (aware\* OR conscious\* OR implicit OR unconscious\*) AND inhibition) AND SU=(Psychology OR Neurosciences & Neurology OR Behavioral Sciences) AND PY=(2005–2015).*" [c] Web of Science advanced search string: "*TS=(("go/no-go" OR "go-nogo" OR"stop-signal" OR "stop signal" OR (go AND "no-go") OR (go AND nogo)) AND reward\* AND inhibition) AND SU=(Psychology OR Neurosciences & Neurology OR Behavioral Sciences) AND PY=(2005–2015).*"

(*Appendices continue*)

Table A4

*Attentional Control (i.e., Attentional Capture by Exogenous Onset Cues or Additional Singletons)*

| Reference | Task(s) | Finding | Confirmation |
|---|---|---|---|
| Context-specificity[a] | | | |
| Anderson (2015) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, but only when presented within the same context | yes |
| Anderson (2015) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, but only when presented within the same spatial context where it was predictive of reward | yes |
| Cosman & Vecera (2013) | Visual search | Attentional capture was modulated by the learning history of attentional sets associated with different task-irrelevant background scenes | yes |
| Cosman & Vecera (2014) | Visual search | Associations between a search target and the most likely color in which it will be presented, modulate attentional capture by a salient color precue | yes |
| Goschy et al. (2014) | Visual search | Attentional capture was reduced for distractor singletons presented at frequent distractor regions | yes |
| Gough et al. (2014) | Spatial cuing | Spatial orienting was modulated by the context-specific proportion of cue validity | yes |
| Thomson & Milliken (2011) | Visual search | Priming of 'pop-out' is modulated by task switching | yes |
| Thomson et al. (2013) | Visual search | Priming of 'pop-out' is modulated by the probability of target repetitions | yes |
| Thomson et al. (2014) | Visual search | Attentional capture was larger for item sets with a high proportion congruency between irrelevant singleton and targets, versus item sets with low proportion congruency | yes |
| Young et al. (2012) | Spatial cuing | Attentional capture for biological versus non-biological threats was modulated by the congruency of the context | yes |
| Operation in the absence of awareness[b] | | | |
| Ansorge & Neumann (2005) | Spatial cueing | Attentional capture was modulated by subliminal spatial primes when matching the observer's intentions | yes |
| Ansorge et al. (2009) | Visual search | Attentional capture was modulated by subliminal color primes | yes |
| Ansorge et al. (2010) | Visual search | Attentional capture was modulated by subliminal color primes when matching the observer's intentions | yes |
| Bauer et al. (2009) | Visual search | Target detection and discrimination is enhanced when a pre-target subliminal flicker was presented at the target's location | yes |
| Cosman & Vecera (2014) | Visual search | Implicit associations between a search target and its likely color modulate attentional capture by a salient color precue | yes |
| Fuchs et al. (2013) | Onset cuing | Attentional capture was modulated by subliminal abrupt-onset cues | yes |
| Fuchs & Ansorge (2012) | Onset cuing | Attentional capture was modulated by subliminal abrupt-onset cues | yes |
| Gough et al. (2014) | Spatial cuing | Spatial orienting was modulated by the context-specific proportion of cue validity when unaware of this manipulation | yes |
| Held et al. (2010) | Visual search | Attentional capture by singletons outside the awareness of the participant | yes |
| Hsieh et al. (2011) | Visual search | Attentional capture by singletons outside of the participants' awareness | yes |
| Lamy et al. (2015) | Visual search | Attentional capture by cues matching the participant's attentional set while using continuous flash suppression | yes |
| Lin et al. (2009) | Visual search | Attentional capture by a looming item on a collision path with the observer in the absence of awareness | yes |
| Lin & Murray (2015) | Spatial cuing | Spatial attention was modulated by exogenous subliminal cues | yes |
| Mele et al. (2008) | Spatial cuing | Spatial attention was not modulated by exogenous subliminal cues | no |
| Mulckhuyse et al. (2007) | Onset cuing | Attentional capture was modulated by subliminal abrupt-onset cues | yes |
| Reuss et al. (2011) | Spatial cuing | Masked arrows drive shifts in attention only when in line with observer's intentions | yes |
| Schoeberl et al. (2015) | Onset cuing | Attentional capture was modulated by subliminal onset cues | yes |
| Thomson et al. (2014) | Visual search | Attentional capture was larger for item sets with a high proportion congruency between irrelevant singleton and targets, versus item sets with low proportion congruency, even without awareness of proportion manipulation | yes |
| Zhaoping (2008; Exp. 1) | Visual search | Eye of origin singletons can capture attention in the absence of awareness | yes |

*(Appendices continue)*

Table A4 (*continued*)

| Reference | Task(s) | Finding | Confirmation |
|---|---|---|---|
| | | Reward-sensitivity[c] | |
| Anderson et al. (2011a) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude | yes |
| Anderson et al. (2011b) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, but extinguished over several hundred trials | yes |
| Anderson & Yantis (2012) | Visual search | Oculomotor capture was larger for previously rewarded items associated with a high versus low reward magnitude | yes |
| Anderson et al. (2012) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, even when tested in an alternative task | yes |
| Anderson & Yantis (2013) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, even when the item features were rewarded over half a year ago | yes |
| Anderson et al. (2013) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, and are maintained when new reward contingencies are introduced | yes |
| Anderson (2015) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, but only when presented within the same context | yes |
| Anderson (in press) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, but only when presented within the same spatial context where it was predictive of reward | yes |
| Ásgeirsson & Kristjánsson (2014) | Visual search | Attentional capture was not modulated by reward on the previous trial | no |
| Bucker, Belopolsky, & Theeuwes, (2015) | Global effect | Oculomotor capture was larger for distractors that signaled high versus low reward, even when rewards were no longer delivered | yes |
| Bucker, Silvis, et al. (2015) | Global effect | Oculomotor capture was larger for distractors that signaled high versus low reward, even when these distractors never served as target, always as distractor | yes |
| Chelazzi et al. (2014) | Visual search | Attentional capture was larger on spatial locations that were associated with a higher reward probability in a previous learning phase | yes |
| Della Libera & Chelazzi (2006) | Global/local or similarity judgment | Negative priming of visual attention was present following high reward only | yes |
| Della Libera & Chelazzi (2009) | Similarity judgment | Shapes previously associated with a higher reward probability sped up categorization, even when the learning phase was five days earlier | yes |
| Failing & Theeuwes (2014) | Spatial cueing | The exogenous spatial cue attracted attention more when its color was previously rewarded more | yes |
| Hickey et al. (2010a) | Visual search | Attentional capture was larger for items that were rewarded on the previous trial | yes |
| Hickey et al. (2010b) | Visual search | Attentional capture was larger for items that were rewarded on the previous trial, especially for reward-sensitive people | yes |
| Hickey et al. (2011) | Visual search | Attentional capture was larger for items that were rewarded on the previous trial, but performance during the reappearance of a distractor did not benefit from rewards on the previous trial | yes |
| Hickey & van Zoest (2012) | Visual search | Oculomotor capture was larger for items that were rewarded on the previous trial | yes |
| Hickey & van Zoest (2013) | Visual search | Oculomotor capture was larger for items that were rewarded on the previous trial | yes |
| Hickey et al. (2014) | Visual search | Attentional capture was larger for locations that were rewarded on the previous trial | yes |
| Hickey et al. (2015) | Visual search | Attentional capture was larger for object categories that were rewarded on the previous trial | yes |
| Hickey & Peelen (2015) | Visual search | Attentional capture was larger for object categories that were rewarded on the previous trial | yes |
| Kiss et al. (2009) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude | yes |
| Kristjánsson et al. (2010) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, and this effect reversed rapidly (six trials) when contingencies reversed | yes |

Table A4 (*continued*)

| Reference | Task(s) | Finding | Confirmation |
|---|---|---|---|
| Laurent et al. (2015) | Visual search | Attentional capture was larger for previously rewarded than for unrewarded items, also when rewarding the feature orientation instead of color | yes |
| Le Pelley et al. (2015) | Visual search | Attentional and oculomotor capture was larger for previously rewarded than for unrewarded items, even when these items were never task-relevant and capture is always counterproductive | yes |
| MacLean & Giesbrecht (2014) | Visual search | Target selection was faster for previously rewarded than for unrewarded items, even when the item features were rewarded over a week ago | yes |
| MacLean & Giesbrecht (2015) | Visual search | Target selection was faster for previously rewarded than for unrewarded items, even when the item features were rewarded over a week ago | yes |
| Mine & Saiki (2015) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude | yes |
| Pearson et al. (2015) | Visual search | Oculomotor capture was larger for previously rewarded than for unrewarded items, despite instructions to ignore rewarded distractors | yes |
| Pool et al. (2014) | Spatial cuing | Spatial cues attracted more attention when previously paired with a reward (chocolate odor), unless the reward was devalued between the learning and test phase | yes |
| Qi et al. (2013) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude | yes |
| Roper et al. (2014) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, and persisted longer in adolescents than in adults | yes |
| Rutherford et al. (2010) | Spatial cuing | Previously rewarded, relative to unrewarded, spatial task cues slowed down subsequent target detection when presented on the same location | yes |
| Sali et al. (2014) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, only when those items were actually predictive of reward during the training phase | yes |
| Theeuwes & Belopolsky (2012) | Visual search | Oculomotor capture was larger for previously rewarded items associated with a high versus low reward magnitude | yes |
| Wentura et al. (2014) | Visual search | Attentional capture was larger for previously rewarded or punished items than for neutral items | yes |
| Yantis et al. (2012) | Visual search | Attentional capture was larger for previously rewarded items associated with a high versus low reward magnitude, even when the item features were rewarded days ago | yes |

[a] Web of Science advanced search string: "*TS=((singleton OR (exogenous AND attention) OR (Posner AND attention) OR (attention AND capture)) AND (context\* OR transfer\* OR specific\* OR context-specific\*)) AND SU=(Psychology OR Neurosciences & Neurology OR Behavioral Sciences) AND PY=(2005–2015).*" [b] Web of Science advanced search string: "*TS=((singleton OR (exogenous AND attention) OR (Posner AND attention) OR (attention AND capture)) AND (aware\* OR conscious\* OR implicit OR unconscious\*)) AND SU=(Psychology OR Neurosciences & Neurology OR Behavioral Sciences) AND PY=(2005–2015).*" [c] Web of Science advanced search string: "*TS=((singleton OR (exogenous AND attention) OR (Posner AND attention) OR (attention AND capture)) AND reward\*) AND SU=(Psychology OR Neurosciences & Neurology OR Behavioral Sciences) AND PY=(2005–2015).*"

(*Appendices continue*)

# Appendix B

## Simulation

In the current paper we propose that performance optimization is the primary target of cognitive control. A system that is not primarily aimed at conflict management but rather on overall performance optimization may nevertheless be successful in overcoming cognitive conflict. This notion was elaborated and supported in a recent paper by Verguts, Vassena and Silvetti (2015). In the following simulation, we illustrate the reversed notion, namely that a system that is primarily aimed at conflict management (indirectly) also optimizes general performance.

The current simulation is based on the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009). Crucially, we manipulated the model's learning rate, which reflects the size of the model's time-integration window across past trials for setting its parameters (i.e., neural network weights). A small learning rate corresponds to a model with a broad integration window across time (i.e., minimal trial-to-trial conflict adaptation). Increasingly higher learning rates lead to increasingly larger emphasis on the more recent trial history in determining conflict adaptation; in the most extreme case (highest learning rate), the cognitive system considers the previous trial exclusively for updating its parameters. If conflict adaptation serves performance optimization, then performance would be a smooth function of learning rate in which some intermediate level of learning rate (time-integration window) optimizes overall performance; hence, neither very high levels of learning rate (i.e., strong adaptation) nor very low levels of learning rate (i.e., minimal adaptation) should be optimal in terms of overall performance. As specified below, we investigate this by fitting a diffusion model on simulated data and zooming in on the drift rate parameter.

## Model Description

The model is similar to the one reported in Verguts and Notebaert (2008), and in particular the version reported in Blais and Verguts (2012). Most specifications here are taken from the latter paper. We implemented a five-stimulus flanker task for 600 trials and 20 subjects. Time in a trial is indexed by $t$; the cascade rate of activation in a trial is denoted by $\tau$. At input, a target and flanker layer are implemented. The activation equation for an arbitrary input unit $i$ (either in the target or flanker layer) is:

$$x_i^{in}(t + 1) = (1 - \tau)x_i^{in}(t) + \tau I_i(t) \qquad (A1)$$

$I_i(t)$ is an indicator function equal to 1 if the stimulus corresponding to that unit $i$ is presented at time $t$, and zero otherwise. To implement residual activation from earlier trials, activation of input units at the start of trial $n$ was set to 40% of the value at the end of trial $n - 1$. This residual activation causes the congruency sequence effect (see Blais & Verguts, 2012, for explanation).

Input units send activation to response units. The activation equation for a response unit $j$ is:

$$x_j^{res}(t + 1) = (1 - \tau)x_j^{res}(t) + \tau\left(\sum_i w_i^{ir} x_i^{in}(t)\right.$$
$$\left(C + \sum_{k=1}^{2} w_{ki}^{ti}(n)x_k^{td}(n)\right) + w^{inh}\sum_{k \neq j} x_k^{res}(t)\right) \qquad (A2)$$

The matrix $w^{ir}$ contains bottom-up weights from the input layers to the response layer. The term $(C + \sum_{k=1}^{2} w_{ki}^{ti}(n)x_k^{td}(n))$ implements top-down attentional weighting from the two attentional units (flanker, target; see Figure 1 in Blais & Verguts, 2012) to the input layers by weight matrix $w^{ti}$ which is adaptively changed across trials $n$. The term $w^{inh}\sum_{k \neq j} x_k^{res}(t)$ reflects response competition. The summation $-w^{inh}\sum_k \sum_{k \neq j} x_k^{res}(t)x_k^{res}(t)$ over response units represents the total amount of response conflict (cf. response conflict unit in Figure 1 of Botvinick et al., 2001).

The activation equation for the control unit is:

$$x^{con}(n + 1) = \lambda_{con}x^{con}(n) + (1 - \lambda_{con})$$
$$\left(-w^{inh}\sum_j \sum_{k \neq j} x_j^{res}x_k^{res} + \beta_{con}\right) \qquad (A3)$$

This equation is applied at the end of each trial $n$. Finally, weights are adapted according to a conflict-modulated Hebbian learning rule:

$$w_{ki}^{ti}(n + 1) = \lambda_w w_{ki}^{ti}(n) + (1 - \lambda_w)(\alpha \times f + \beta_w) \qquad (A4)$$

The term $f$ implements the conflict-modulated Hebbian term:

$$f = \left(x_{con}(n) - \overline{x^{con}}\right)x_i^{in}(t)\left(x_k^{ti}(n) - 1/2\right) \qquad (A5)$$

where $\overline{x^{con}}$ denotes the mean activity of the control unit up to trial $n$. When both difference terms in (A5) are negative, the equation is set to zero. Weights $w^{ti}$ are only adapted between attentional units and their corresponding input layer units and are restricted to be nonnegative.

Parameters were taken from Blais and Verguts (2012): $\tau = 0.1$, $w^{inh} = -0.5$, $C = 0.7$, $\lambda_{con} = 0.8$, $\beta_{con} = 1$, $\alpha = 20$, $\beta_w = 0.5$. The activation of the target attention unit was set at 1, and that of the flanker attention unit at 0.3. The initial strength of each attention unit to its corresponding input units (i.e., initial entries in matrix $w^{ti}$) was 0.5. The strength of input-response connections for the target layer equals 1 (e.g., from stimulus 1 to response "1"; matrix $w^{ir}$); the strength of input-response connections for the flanker layer equals 1.1. In each trial, activation of the input and response units was updated according to Equations (A1) and (A2) until one of the response units reached a threshold value of 0.6. The corresponding response was taken to be the model's response choice and the time needed to reach that unit was taken to be the model's response time. The qualitative pattern of results was robust to changes in these parameters.
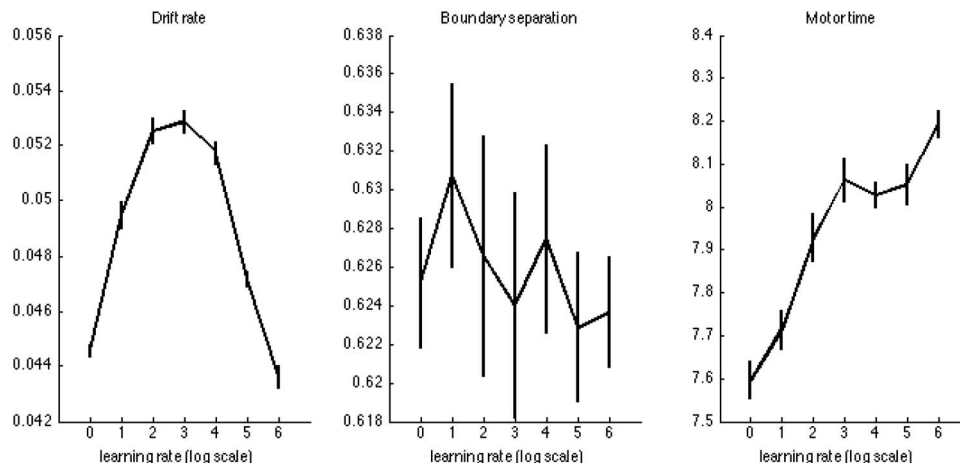
*Figure A1.* Estimated diffusion model parameters on cognitive control model simulated data. *x* axis represents learning rate on a log scale ($-\log(1 - \lambda_w)$). Error bars are 1 *SE* (across 20 simulated subjects).

The parameter of interest manipulated here is the attentional weight learning rate $\lambda_w$ (Equation (A4)). Its values were scaled in equidistant logarithmic steps, in particular, $\lambda_w = 0, 0.9, 0.99, \ldots,$ up to $1-10^{-6}$ (*x* axis, Figure A1).

## Data Analysis

We fitted a diffusion model on each (of 20) simulated subjects' data using the equations from Wagenmakers, Van der Maas, and Grasman (2007) to extract three parameters: drift rate, boundary separation, and motor/encoding time. Drift rate is a measure of the efficiency of a cognitive process (Ratcliff, 1978); higher drift rates means better (cognitive) performance. This is the critical parameter for current purposes. Boundary separation is a "strategic" parameter, determining speed–accuracy trade-off (e.g., Ratcliff, 1978), whereas motor/encoding time is (as the name suggests) unrelated to the decision process. Hence, we predict that an optimal control setting (intermediate learning rate in the cognitive control model) can also optimize performance (drift rate in the diffusion model).

## Results

The fitted diffusion model parameters are shown in Figure A1. The *x* axis in each panel represents learning rate on a logarithmic scale. Figure A1 (left panel) shows the mean drift rate for each learning rate and demonstrates that neither a static configuration (very low learning rate, no conflict adaptation) nor an extremely quickly adapting system (very high learning rate) optimizes performance (i.e., cognitive efficiency). Instead, an intermediate learning rate is optimal, suggesting that indeed the mechanism dealing with conflict management also optimizes performance. In contrast, learning rate does not systematically influence boundary separation (Figure A1, central panel). Finally, the right panel of Figure A1 shows how motor/encoding time is systematically influenced by learning rate—but not in an inverted-U form like is the case for drift rate.