Getting a grip on cognitive flexibility

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Abstract

Cognitive flexibility refers to the ability to quickly reconfigure our mind, like when we switch between different tasks. This review highlights recent evidence showing that cognitive flexibility can be conditioned by simple incentives typically known to drive lower-level learning, such as stimulus-response associations. Cognitive flexibility can also become associated with, and triggered by, bottom-up contextual cues in our environment, including subliminal cues. Therefore, we suggest that the control functions that mediate cognitive flexibility are grounded in, and guided by, basic associative learning mechanisms, and abide by the same learning principles as more low-level forms of behavior. Such a learning perspective on cognitive flexibility offers new directions and important implications for further research, theory, and applications.

Keywords: Cognitive flexibility, Cognitive control, Associative learning, Reinforcement learning, Task switching

Much of human behavior is characterized by the extraordinary ability to quickly reconfigure our mind, and switch between different tasks: We can swiftly shift our focus from color and fabric, when sorting dirty clothes for laundry, to shape, when searching for socks in a pile of clothes fresh from the dryer. This ability, often referred to as cognitive flexibility, has been widely recognized as a core function of cognitive control (Diamond, 2013), is of increasing importance in this digital age of multi-tasking (Eshet-Alkalai, 2004), and anomalies in flexibility are thought to characterize various clinical disorders (Geurts et al., 2009; Meiran et al., 2011). Cognitive flexibility has been studied on many different levels, including individual differences (Hommel & Colzato, 2017) and developmental changes (Dajani & Uddin, 2015). However, while most psychologists agree on the kind of behaviors that require cognitive flexibility, we know little about how this control function is regulated: how do we know when to be flexible, and how much?

Here, we will highlight recent work from the task switching literature that offers important new insights into how cognitive flexibility might be controlled. Specifically, after a brief introduction on cognitive flexibility and task switching, we will review evidence showing that the high-level ability to reconfigure the mind can be conditioned by simple incentives, and triggered by contextual features in our environment, possibly even outside awareness. Finally, building on these findings, we will promote a learning perspective on cognitive flexibility.

Cognitive flexibility: the pinnacle of cognitive control?

According to Diamond (2013), cognitive flexibility is one of the three core cognitive control (or executive) functions, next to inhibition and working memory.

Cognitive control mechanisms allow us to use internal goals and current context to guide information processing “top down” (e.g., Miller & Cohen, 2001). For example, we can combine the contextual information of seeing a traffic agent with our goal of personal safety to impose a new set of rules on how we link stimuli to actions (i.e., focus on the agent’s hands rather than the malfunctioning traffic lights). Imposing control in this manner involves overriding well-learned, habitual actions (e.g., braking when the traffic light turns red) and, accordingly, cognitive control has traditionally been seen as diametrically opposed to basic associative learning mechanisms that mediate the binding of stimuli to responses in routine behavior (Norman & Shallice, 1986). While associative learning is generally thought to produce fast, automatized stimulus-response links that can run unsupervised (and possibly unconsciously), cognitive control is thought to require volition and attention to produce slow but strategic action (e.g., Norman & Shallice, 1986; Diamond, 2013).

In this conceptualization, cognitive flexibility may possibly be considered the pinnacle of cognitive control: Other control processes are important to maintain and protect our current goals and task sets (e.g., by selectively attending to goal-relevant stimuli and inhibiting habitual responses), but it is one's overarching ability to flexibly change these goals and task sets that produces adaptive behavior. Cognitive flexibility can thus be seen as a form of “meta-control” (Goschke, 2003; Hommel, 2015). However, casting cognitive flexibility as a higher-order control process naturally invites the question of how this ability to change task sets is regulated: Absent the assumption of a homunculus, what controls cognitive flexibility? Intriguingly, recent work suggests that flexibility can in fact be guided by “low-level” associative learning processes.

Task switching as a marker of cognitive flexibility

Our brief review will focus on regulation of cognitive flexibility in the context of studies investigating task switching (for reviews, see Kiesel et al., 2010; Vandierendonck et al., 2010). Cognitive flexibility has also been studied using creative problem solving, or rule reversal learning paradigms, like the Wisconscin Card Sorting Test. However, these paradigms provide less experimenter control over when the actual change in task sets occurred (see also, Geurts et al., 2009). There is also conceptual overlap between task-switching research and the study of working memory updating, though the latter tends to focus primarily on changing “items” in (declarative) working memory than on changing (procedural) task rules (Hazy et al., 2006).

The task switching literature investigates switching between task sets. Task sets can be considered a configuration of context-dependent production (“if, then”) rules that are actively maintained in order to guide our current behavior. For example, when we want to call our friend, we use a given set of rules to navigate through our phone, which define our task set. While certain components are often shared across task sets, it is their associations with the different rules and goals that make task sets unique (e.g., pushing a number to dial a phone number versus pushing a number to change floors in an elevator).

Using paradigms in which participants have to switch between two or more tasks, task switching studies typically focus on the *switch cost*: slower and less accurate performance on task switches than task repetitions. The switch cost has been interpreted as an index of cognitive control processes required for reconfiguring the task set (Rogers & Monsell, 1995) and/or resolving interference from the previously active task set (Allport et al., 1994). As a more tonic and voluntary marker of cognitive flexibility, recent studies have also begun emphasizing the *switch rate*: how much people choose to switch tasks in a free choice environment (Arrington & Logan, 2004).

A possible role for associative learning in task-switching was initially only investigated at the level of task sets: studies showed that task sets can be bound to, and be primed by, task-relevant (e.g., Waszak, Hommel, & Allport, 2003) and -irrelevant stimuli (e.g., Mayr & Bryck, 2007), and can be reinforced following reward feedback (e.g., Schiffer et al., 2014), similar to stimulus-response associations (for a review, see Abrahamse et al., 2016). More recently though, there has been a realization that learning may not only promote the retrieval of one task set over another, but could also modulate the preparedness to switch sets *per se*. For instance, Dreisbach and Haider (2006) observed that a higher switch-likelihood (a higher proportion of task switches vs. repetitions in a block of trials) resulted in reduced switch costs. This opened the door to asking whether “low-level” learning mechanisms can shape cognitive flexibility.

Cognitive flexibility can be conditioned

Cognitive control functions are assumed crucial for overriding habitual behavior, like strongly conditioned responses, but can control functions themselves be subject to conditioning by reward? Although recent research has begun to investigate interactions between cognitive control and reward processing (for reviews, Botvinick & Braver, 2015; Notebaert & Braem, 2015), most of these studies presented explicit reward motivation *cues* before task execution, thus focusing on the effects of anticipating reward on cognitive control. Possibly, this focus on explicit reward cues was motivated by the idea that top-down, strategic control processes can only be up-regulated proactively by explicit, preparatory cues. In contrast, the reinforcement learning literature usually focuses on the (automatic) strengthening of behavior following reward *feedback* (Sutton & Barto, 1998).

As a first step towards connecting these disparate literatures (see also, Umemoto & Holroyd, 2015), we recently demonstrated that the act of task switching can be conditioned by reward (Braem, 2017). In a first phase of the experiment, cues told participants which task had to be performed on each trial (i.e., cued task phase), and people were rewarded more when performing a task switch than a task repetition (Figure 1A). In a second phase, participants were free to choose which task to perform, and no more rewards were delivered. Interestingly, despite the fact that participants were unaware of the biased reward allocation in the first phase, they now showed more voluntary task switching behavior (Figure 1B), suggesting that cognitive flexibility can be conditioned. In a similar vein, another recent study showed that presenting participants with more task switches than repetitions during a cued task phase, influenced subjects’ choice to be more flexible in a subsequent voluntary task choice environment (i.e., performing more voluntary task switches; Fröber & Dreisbach, 2017).

Together, these studies suggest that the choice to be cognitively flexible is very susceptible to its recent (reinforcement) learning history. These studies are also congruent with a much older line of research in behavioral psychology, where (animal) psychologists demonstrated that variability in behavior (i.e., responding in a less predictable manner) is a behavior that in itself can be selectively reinforced (for a review, see Neuringer, 2002). Future studies should address whether this type of reinforced behavioral variability relies on the same mechanisms as those underlying task switching.

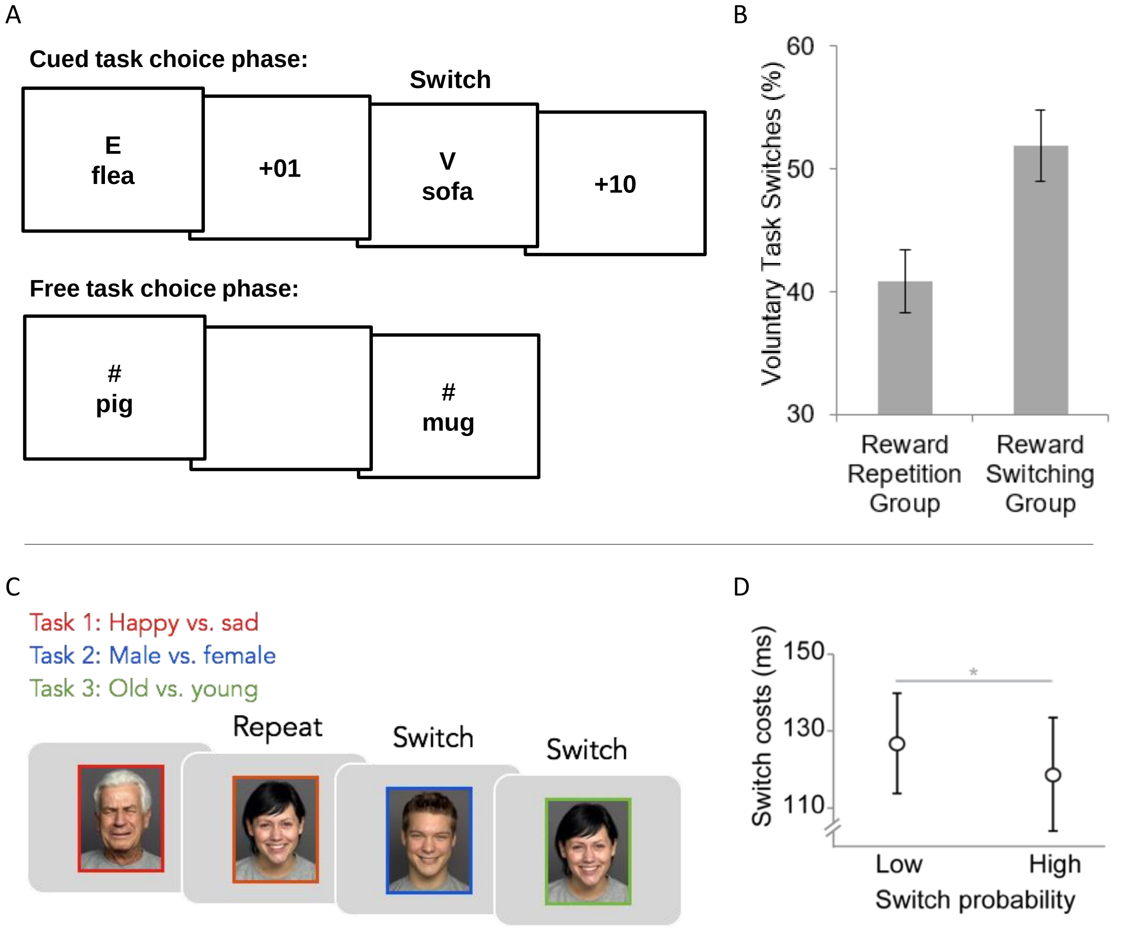

Figure 1: An illustration of the studies by Braem (2017) and Chiu and Egner (2017, Experiment 3). **A**. In Braem (2017), participants had to categorize words according to animacy (living or non-living) or size (larger or smaller than a basketball), depending on whether the task cue was a vowel or a consonant. Unbeknownst to them, depending on which group they were assigned to, they had an increased chance of obtaining a big reward following task switches versus task repetitions. In a second phase, no more rewards were given and participants were free which task to perform. **B**. The group rewarded more for task alternations showed more spontaneous task switching performance. **C**. In Chiu & Egner (2017), participants had to perform one out of three tasks (categorizing faces according to gender, age, or emotion) depending on the color surrounding a picture of a face. Crucially, some faces were presented more when tasks

switched, while others were presented more when tasks repeated. **D**. The pictures associated to a higher likelihood of task switching showed increased task switching performance (i.e., smaller task switch costs). Reprinted with permission.

Cognitive flexibility can be triggered by contextual cues

A traditional assumption of cognitive flexibility (and cognitive control more broadly) is that it is generalizable. Thus, the processes responsible for task switching are not thought to be specific to particular tasks but to be shared among all possible task switching conditions. Consequently, many scholars have hypothesized that the effects of training people on being more cognitively flexible in one task context should transfer to other tasks measuring cognitive flexibility. However, recent meta-analyses have demonstrated that cognitive training studies rarely find transfer (e.g., Simons et al., 2016).

In contrast, associative learning processes are thought to be trigger-specific in nature, as learned associations are known to bind to the context in which they occur (Pearce & Bouton, 2001). In behavioral psychology, this is often referred to as *stimulus control*, but we will speak of the *context-specificity* of learned behavior. For example, the habit of smoking can be very context-specific: environments that have been more frequently associated with smoking in the past will induce a higher urge to smoke, independent of the availability of cigarettes (Dols, van den Hout, Kindt, & Willems, 2002). Intriguingly, recent studies have documented that the same class of phenomena can be observed in relation to cognitive control settings. For instance, if a spatial context (like screen location) is predictive of more challenging task demands, over time this high-demand context comes to implicitly cue the retrieval of the appropriate attentional set, thus making participants better at meeting high task demands in that spatial context (for reviews, see Bugg & Crump, 2012; Egner, 2014).

Importantly, recent studies have extended these findings of “context-control learning” to the case of cognitive flexibility. For example, it has been shown that switch costs can be reduced for stimuli that are presented at a screen location associated with a higher likelihood of task switches (relative to repetitions), even when people are unaware of this contingency (Crump & Logan, 2010; for a similar observation in attention shifting, see Sali, Anderson, & Yantis, 2015). In a similar vein, Farooqui and Manly (2015) demonstrated that subliminally presented (i.e., not consciously perceived) cues signaling a higher likelihood of task switches were followed by smaller task switch costs.

If the readiness to switch between different tasks can be triggered by contextual cues, like location, it should also be possible to bind switch-readiness to specific task stimuli. We tested this hypothesis by linking particular stimuli to the need to update tasks more or less frequently (Chiu & Egner, 2017; see also Leboe et al., 2008). By employing three different task sets (see Figure 1C), we could demonstrate that stimuli (here, specific individuals’ faces) associated with task switches did indeed facilitate task switching, and that they did so irrespective of which task was being switched to (Figure 1D). This suggests that what participants learned was to associate specific cues with a general readiness to switch between tasks rather than to switch to one particular alternative task. This finding emphasizes a key distinction in the effects of learned stimulus-control vs. stimulus-response associations: while the latter are *specific* (e.g., promoting a particular motor response), the former are *generalizable* (here, aiding the switch to any other task) (Egner, 2014). The extent of this generalizability (e.g., to other measures of cognitive flexibility), however, remains an interesting avenue for future research.

Taken together, these findings show that, through learning, stimuli in our environment can be bound to the processes underlying cognitive flexibility (e.g., to an “updating threshold”, cf. Goschke, 2003), and eventually help triggering cognitive flexibility bottom-up, even subliminally. By relying on these fast associative learning processes, the contextual triggering of cognitive flexibility may allow for a more efficient and less effortful allocation of control strategies.

A learning perspective on cognitive flexibility

In trying to answer what controls cognitive flexibility, the above studies demonstrate that, much like simple motor responses, cognitive flexibility is highly sensitive to the environment it operates in, and rewards that follow it. However, in our view, the impact of these findings has remained underappreciated in the broader literature, likely because they do not fit with more traditional notions of cognitive control as being in competition with bottom-up associative behavior. Many psychologists still ascribe cognitive flexibility to independent, supervisory, or "executive" control systems that correct low-level behavior, without specifying regulatory mechanisms for employing these functions in an adaptive manner (e.g., Diamond, 2013).

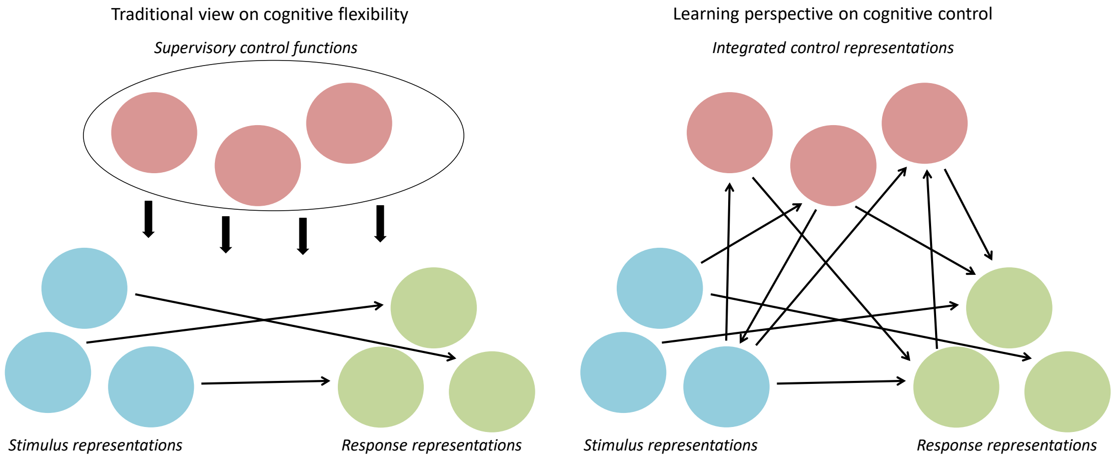

Figure 2: An illustration of a more traditional view versus a learning perspective on cognitive flexibility. The left side shows a more traditional view, where stimulus-response learning and more abstract task sets are thought to be supervised by an independent set of cognitive control functions. The right side depicts a learning perspective, which emphasizes the grounding of cognitive control in associative learning. In both views, cognitive flexibility describes the general ability to flexibly switch between different concepts or task sets, and would result from one or more control functions/representations. Therefore, a learning perspective maintains these same "general" control representations (or control settings), but their context-specificity or lack of transfer is explained by their associations with more low-level features of information processing, rather than, for example, a multitude of different control functions for each context separately. This depiction is only meant to illustrate a way of thinking on cognitive control (for related illustrations and arguments, see Abrahamse et al., 2016; Eisenreich et al., 2017).

Instead, we believe that these findings call for an alternative perspective where the functions which allow us to be flexible are guided by basic (associative) learning, and abide by the same learning principles as more low-level forms of behavior do. This view is consistent with recent theoretical perspectives on the regulation of other control functions, like conflict-control (Abrahamse, Braem, Notebaert, & Verguts, 2016; Egner, 2014), which has been effectively modeled using basic reinforcement learning rules (e.g., Botvinick et al., 2001). The basic premise of this perspective is that, rather than seeing cognitive flexibility as originating from a standalone module (or brain region) that intervenes - *deus ex machina* – to solve problems in lower-level associative processing, the processes underlying cognitive flexibility are grounded in the learning framework (and associative network) as simple stimulus-response associations (Figure 2). Thus, while cognitive control processes are “higher-level” in that they can produce generalizable benefits, their regulation must be understood in terms of basic associative learning processes.

Conclusion

In sum, we aimed to illustrate how recent observations break with traditional ideas on cognitive flexibility, by showing how cognitive flexibility can be conditioned and bound to contextual cues. We believe the literature is in need of a paradigmatic shift in how psychologists understand cognitive flexibility, and cognitive control more broadly.

A learning perspective on cognitive flexibility could provide new challenges for computational models of task switching (e.g., Holroyd & McClure, 2015), and theorizing about impairments in cognitive flexibility in certain neurocognitive disorders (e.g., autism, Geurts et al., 2009; OCD or depression, Meiran et al., 2011). Moreover, the conditioning and contextual cuing of cognitive flexibility could also offer promising applications for facilitating behavioral change, as other forms of conditioning have (e.g., De Houwer et al., 2001). For example, in training people to be more cognitively flexible, one could take advantage of its context-sensitivity by training people in the environments where flexibility is most required. Last, we only focused on learning via experience, but recent studies have shown that learning via instructions can also result in automatic stimulus-response associations (e.g., Meiran, Liefooghe, & De Houwer, 2017). Therefore, an interesting hypothesis to test would be whether instructed stimulus-control assocations would also result in the kind of automaticity reviewed here.

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Recommended Reading

Abrahamse, E., Braem, S., Notebaert, W., & Verguts, T. (See References). Provides a more comprehensive review of the empirical literature, and outlines the broader implications of an associative learning perspective on cognitive control.

Egner, T. (See References). Gives a more detailed description of the explanatory value of a learning perspective in the conflict adaptation literature, where more studies already investigated the context-specificity of cognitive control.

Geurts, H. M., Corbett, B., & Solomon, M. (See References). Reviews the literature on cognitive flexibility from a clinical perspective (i.e., in autism), and, in doing so, critically evaluates the concept of cognitive flexibility and how to best study it.

Ionescu, T. (2012). Exploring the nature of cognitive flexibility. *New ideas in psychology, 30(2),* 190-200. While outside the scope of the current brief review, this theoretical review offers an interesting discussion on the different uses of the term cognitive flexibility (e.g., as a skill versus property of the cognitive system).

Neuringer, A. (See References). Reviews an interesting, related line of research from behavioral psychology that studied the conditioning of variability in behavior.

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