How Performance-Contingent Reward Prospect and Positive Affect Modulate Cognitive Control

Kumulative Inaugural-Dissertation zur Erlangung der Doktorwürde

der Fakultät für Humanwissenschaften

der Universität Regensburg

vorgelegt von

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(geb. HEFER)

aus Fürstenfeldbruck

Regensburg 2020

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ACKNOWLEDGMENT

First, I want to thank Prof. Dr. Gesine Dreisbach for her support, inspiration, ideas and her faith and trust in me to carry out this project successfully. To be part of your research team was a great and valuable experience. Under your supervision, I have developed a lot and I will always be happy to think back on my time at the University of Regensburg.

A special thanks goes to my colleague Dr. Kerstin Fröber who always had open ears for all my questions. I am also very grateful to Claudia Lehnes as well as my colleagues Anja, Katrina, Johanna, Katrin, Vanessa, Jonathan, and Felix with all of whom I enjoyed inspiriting and motivating discussions. Many thanks to all research assistants for their help with data collection and to all (non-) students who participated in my studies. Finally, I want to thank my family who made it possible for me to go to University and who always supported me in my decision to do my PhD.

PREFACE

When asked which skills enable successful performance at work, school, or in traffic, a layman would name factors or skills like intelligence, concentration capacity, or multitasking ability. In the field of general psychology, these qualities are encompassed by the broader concept of "cognitive control", which describes cognitive processes that make adaptive and goal-directed behavior possible in a constantly changing environment. One illustration of a changing environment is at work, where not every day is the same: On some days it is easy to concentrate and to make progress on, for example, writing an article. On other days, however, it is harder to concentrate on this task because of multiple distractions like phone calls or spontaneous meetings. Because of these frequent environment changes, effective cognitive control relies on the implementation of two antagonistic cognitive control strategies: stability and flexibility. Stability involves maintaining goals (e.g., writing an article) and shielding them from distraction (e.g., background noise or phone calls). Flexibility, on the other hand, involves the updating of goals in response to significant changes (e.g., leaving the office because of fire alarm). Individual factors, such as age, intelligence or cultural background, and situational factors, such as task context, affect the weighting of these complementary control strategies. Importantly for the present thesis, there is growing evidence that affect (e.g., having a positive or negative mood) and motivation (e.g., being driven to earn a reward) have different effects on the balance between cognitive stability and flexibility. Since affect and motivation are omnipresent in our everyday life, it is of great interest to determine their influence on cognitive performance. Although most research on the effect of reward motivation on cognition demonstrated performance benefits, other studies showed detrimental effects of reward. Also, there are inconsistent findings in the research area of positive affect-cognition interaction. Moreover, existing literature on this topic has not always sufficiently addressed how different methods for eliciting positive affect (e.g., positive pictures vs. reward incentives) might lead to different effects on cognition. Thus, the purpose of the present dissertation was to further disentangle the motivational (induced via performance-contingent reward) and affective (induced via positive pictures low in arousal) modulation of antagonistic control strategies. To this end, **Studies 1 and 2** investigated the influence of performance-contingent reward on cognitive control, whereas **Study 3** clarified the influence of positive affect on cognitive control.

The following introduction will define the term cognitive control and outline relevant theories. The introduction will also highlight empirical results as well as open questions in the research field of positive affect-cognition and reward motivation-cognition interaction (Part I). The main part of the thesis will include three empirical studies that address some of these open questions (Part II). All studies have been published in peer-reviewed journals over the last three years and haven been copied in their last accepted preprint version with permission from the publishers. For the sake of readability, the reference lists have been summarized into one bibliography at the end of the thesis. The Supplemental Materials (published online) of Studies 1 and 2 can also be found at the end of the thesis. The numbering of the experiments, tables, footnotes and figures has been adjusted to fit the thesis as a whole. In some places, the layout was adapted to fit to the rest of the thesis. Otherwise, the manuscripts have not been changed. The thesis closes with a summary of the main findings, a general discussion, and a final conclusion about the motivational and affective modulation of cognitive control (Part III).

CONTENT

ABSTRACT

Prior research suggests that performance-contingent reward increases goal maintenance and cognitive stability, whereas positive affect decreases cognitive stability in favor of a more flexible control mode. The aim of the present thesis was to further investigate the motivational and affective modulation of the balance between these antagonistic control modes, cognitive stability and flexibility. To this end, the AX-Continuous Performance Task was used, – in both its standard and modified version. **STUDY 1** once again replicated the typical finding that reward motivation increases cognitive stability. Moreover, it demonstrated that this reward effect comes at the cost of decreased flexibility: Participants who received performance-contingent rewards showed rigid cue usage even when reward was no longer available and cueing information changed from highly predictive to nonpredictive. **STUDY 2** was designed to discover reasons for the maladaptive perseveration found in Study 1. Results of three experiments demonstrated that reward prospect promotes the usage of any information that might be relevant for preparatory behavior. **STUDY 3** replicated the findings that positive affect increases cognitive flexibility. However, this positive affect effect was vulnerable to strategic influences, which developed with increasing time on task. All results will be discussed in the light of current affect and reward motivation research.

PART I

INTRODUCTION

Cognitive Control

The term cognitive control is widely used in the psychological literature and describes the ability to coordinate and adjust thoughts and actions in accordance with internally maintained goals. In other words, cognitive control allows people to behave in a goal-consistent manner in a variety of situations, ranging from simple decisions (e.g., choosing an ice cream flavor) to highly complex decisions with consequences for the future (e.g., choosing a profession; Gratton, Cooper, Fabiani, Carter, & Karayanidis, 2018a). One of the most central aspects of cognitive control is the ability to favor weaker, but task-relevant information against stronger, but task-irrelevant information (Miller & Cohen, 2001). There are many situations in which behavior depends on cognitive control, including shielding goals from irrelevant information (e.g., concentrated studying for an exam while ignoring distraction from the environment), inhibition of habits or automatic reactions (e.g., refraining from smoking), flexibly switching between several tasks or goals (e.g., switching between answering the phone, writing emails and talking to colleagues), regulating emotions (e.g., to control anger), delaying gratification (e.g., refraining from a current pleasure in favor of a long-term goal) and, with special interest to the present thesis, maintaining (e.g., this friend likes milk in his coffee) and updating information in working memory (e.g., this friend switched to a vegan diet). In short, cognitive control is crucial for what we call intelligent behavior (Miller, 2000; a very detailed overview about cognitive control can be found in Egner, 2017a). The following section provides an overview and short historical perspective of cognitive control in order to briefly answer three important questions: What is cognitive control? How is cognitive control controlled? How is the balance between complementary control modes modulated? The third question is of special interest and will further be answered in the course of the present thesis. Finally, I will move to a more detailed description of two important concepts of cognitive control that are applied in the present thesis.

Overview of Cognitive Control

Interest in investigating how intentional actions are controlled began more than 100 years ago (Ach, 1910; James, 1890). The concept of cognitive control was first introduced by Miller, Galanter, and Pribram (1960) and further investigated by Atkinson and Shiffrin (1968), Posner and Snyder (1975), Schneider and Shiffrin (1977) as well as Shiffrin and Schneider (1977). The authors focused on the dichotomy between controlled (intentional or goal-driven) and automatic (stimulus-driven, involuntary) processes[1]. Controlled processes are assumed to be slower to execute, to be conscious, to be executed only serially, to interfere with other processes, and to rely on a limited-capacity processing mechanism. In contrast, automatic processes are the result of practice, work in parallel, do not depend on capacity-limited attentional processes, are not prone to interference with other processes, and are unconscious. A classic example of this dichotomy is the Stroop task in which participants must name the ink color of color words. Word reading is an automatic process, whereas color naming is a controlled process (Stroop, 1935). If color word and ink color do not match (e.g., the word green is written in blue), response times (RTs) increase because color naming requires top-down control to override the prepotent response from the stronger word reading pathway (Posner & Snyder, 1975). However, research over the last decades has questioned the automatic vs. controlled processes dichotomy (cf. Cohen, 2017; Moors, 2016; Neumann, 1984). For instance, in experiments investigating subliminal response priming (e.g., Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003) and semantic priming (e.g., Schütz, Schendzielarz, Zwitserlood, & Vorberg, 2007), which are prototypical examples of automatic processes, even heavily-masked primes can affect behavior implying that the prime is processed to some degree. It thus seems that cognitive control can be prompted by events of which actors are not aware (Kiefer, 2007, 2012; Kunde, Reuss, & Kiesel, 2012). Consequently, cognitive control does not seem to necessarily require awareness (for an overview see Hommel, 2007). Daily life examples further contradict such a strict dichotomy; for instance, even highly automatic behavior (e.g., driving home from work) is not carried out in an automatic fashion whenever circumstances suggest it (e.g., changing the route home to do shopping; Goschke, 2003). Furthermore, processes can gradually become automatic as a result of conscious practice (Hommel, 2007). It thus seems that there is no strict distinction possible between controlled and automatic processes. Therefore, a more current view is that these processes define the ends of a continuum (Cohen, 2017). But if it is not the person who decides when to engage in cognitive control (assuming that cognitive control processes are not necessarily conscious), the question of who activates cognitive control when needed arises ("homunculus problem", e.g., Miller & Cohen, 2001). To answer this question, new theories introduced the idea of a central executive, that coordinates lower-level sensory and motor

[1] See Posner (1978) for a similar dichotomy between endogenous or top-down control (driven by the current goal of the observer) and exogenous or bottom-up control (driven by physical characters of the scene like stimulus salience) of attention (Awh, Belopolsky, & Theeuwes, 2012).

processes in line with an internal goal. Several theoretical models use this central executive concept to explain how cognitive control is achieved. One theory stems from Norman and Shallice (1986) who proposed an attentional control framework of executive functioning (“supervisory attentional system”). Here, the supervisory attentional system monitors for processing conflicts and intentionally biases action in favor of current goals. Nevertheless, the model does not resolve the “homunculus problem”. Subsequent theories replaced the concept of a homunculus with the proposal that cognitive mechanisms enable different brain modules to interact with each other. There is a large amount of research suggesting the prefrontal cortex (PFC) – which is the cerebral cortex covering the front part of the frontal lobe – as the neural basis of cognitive control, because of its role in linking different brain regions (e.g., Goschke, 2013; Koechlin, Ody, & Kouneiher, 2003; Miller & Cohen, 2001). The PFC is highly interconnected with sensory neocortical and motor systems and a wide range of subcortical structures. Moreover, the PFC projects back to these regions allowing it to exert control over processing in other brain regions (cf. Miller, 2000). These anatomical findings converge with more recent studies showing that the PFC is involved in processes typically summarized under the term cognitive control (Fuster, 2009), such as learning new instructions (Ruge & Wolfensteller, 2010), flexibly adjusting behavior (for a review see Ruge, Jamadar, Zimmermann, & Karayanidis, 2013), or maintaining task-relevant information (D’Ardenne et al., 2012). In fact, if the PFC is damaged, it especially affects performance in tasks that require cognitive control (Miller, 2000). For instance, patients with lesions in the PFC may show perseverative or utilization behavior (for a more detailed overview about how lesions in the brain can affect cognitive control see Fellows, 2017)[2].

Although we are closer to understanding the neural underpinnings of cognitive control, the question of *whether* and *when* cognitive control is recruited is still not answered. One theory that addresses the important questions on what basis cognitive control is recruited, how its influence is modulated or optimized, and on what basis cognitive control is withdrawn, is the Conflict Monitoring theory (CMT, Botvinick, Carter, Braver, Barch, & Cohen, 2001). The central assumption of this theory is that the anterior cingulate cortex (ACC) monitors conflicts in information processing and signals the demand for increased control to the PFC, which then exerts a top-down influence on a wide range of brain processes (Miller, 2000). Behavioral and neural evidence for the CMT comes from work by Kerns et al. (2004), who demonstrated a

[2] An overview of recent neuroscience research that has found specific brain networks that contribute to different aspects of cognitive control can be found in Gratton, Sun, and Petersen (2018b).

reduced interference effect (worse performance on incongruent compared to congruent trials) following incongruent Stroop trials compared with congruent Stroop trials. The finding of reduced interference following incongruent trials (compared with following congruent trials) is called conflict adaptation effect or congruency sequence effect (CSE; cf. Gratton, Coles, and Donchin, 1992), and has been replicated in numerous studies (for a more detailed discussion on the CSE see Egner, 2007, 2014, 2017b). These behavioral adjustments following conflict were associated with increases in PFC activity which in turn was related to ACC activity on the preceding conflict trial (Egner, 2017b). Thus, the results support the role of ACC conflict monitoring in the engagement of cognitive control (for a critical review on the CMT, see Schmidt, 2019). More recent work has demonstrated that cognitive control can also be mobilized by task difficulty (e.g., low perceptual fluency) even in the absence of response conflicts (Dreisbach & Fischer, 2011). Importantly for the present thesis, reward anticipation also increases cognitive control by increasing response preparation and usage of contextual information, which Braver coined the *proactive* component of cognitive control (Braver, 2012; Chiew & Braver, 2014; Fröber & Dreisbach, 2014).

To conclude, in view of the challenges cognitive control has to face (e.g., conflict monitoring, detection, and adjustment), it becomes increasingly clear that it cannot be viewed as a unitary process. There exist a lot of theories that all propose multiple subcomponents of control (e.g., conflict monitoring, detection, and adjustment in Botvinick et al., 2001, or updating, shifting, and inhibition in Miyake et al., 2000). For instance, Gratton and colleagues (2018a) summarize the most important subcomponents of cognitive control as follows: Access to representations of currently possible task goals, goal selection, response planning, monitoring/orienting mechanisms, and inhibition/suppression of no-longer-appropriate task goals. It becomes evident that the subcomponents of cognitive control are partly antagonistic in nature, which brings us to the third question: How is the balance between complementary control modes (i.e., cognitive stability and flexibility) modulated? The present thesis focuses on the dilemma that, on the one hand, goal-directed behavior requires that goals (e.g., studying for an exam) are maintained and shielded from distraction (e.g., the desire to go outside and to enjoy the nice weather). On the other hand, however, significant changes in the environment (e.g., an awaited phone call) require the flexible updating of goals and the disengagement from a currently active goal. These antagonistic control modes are termed cognitive stability and cognitive flexibility (Dreisbach & Fröber, 2019; Dreisbach & Goschke, 2004; Goschke, 2003, 2013; Goschke & Bolte, 2014; Hommel, 2015). Broadly speaking, the present thesis follows the idea that adaptive cognitive control requires a balance between maintaining and shielding goals from competing responses (stability) and the flexible adjustment of goals in response to significant changes (flexibility). Another important theoretical basis for the present thesis is the *Dual Mechanisms of Control* (DMC) framework (Braver, 2012) which distinguishes between the antagonistic control modes of proactive and reactive control. Both concepts will be described in the following section.

The Flexibility-Stability Balance

Considering the challenges cognitive control has to face (e.g., to maintain and update task-relevant information, to shield goals against distraction and irrelevant information, to flexibly shift between goals and tasks in response to significant changes), it becomes clear that a dynamic interplay between different control modes (e.g., focused vs. broad attention) is necessary for adaptive behavior. One influential theory on cognitive control differentiates between cognitive stability and flexibility (Dreisbach & Fröber, 2019; Dreisbach & Goschke, 2004; Goschke, 2003, 2013; Goschke & Bolte, 2014; Hommel, 2015). According to this theory, we have two antagonistic control modes: Without the ability to maintain goal-relevant information and to shield it from distraction (cognitive stability), we would be slaves to our habits and current needs. Without the ability to flexibly switch between different tasks and goals (cognitive flexibility), our behavior would be highly inflexible (Dreisbach & Goschke, 2004). It becomes clear that both control modes come along with complementary costs and benefits. For instance, cognitive stability prevents interference and helps with focusing on relevant information while suppressing irrelevant information, but it increases the risk of perseverative behavior and reduces background monitoring. Conversely, cognitive flexibility facilitates noticing task-irrelevant but important stimuli and task changes, and it facilitates switching between alternative actions, but it increases the risk of impulsive actions, distractibility, and interference (Goschke & Bolte, 2014). Thus, according to the stability-flexibility dilemma, increased cognitive stability should be beneficial as long as the task conditions remain constant, but it should incur a cost when task conditions change. There is indeed evidence for these complementary benefits and costs: Response conflicts trigger an increase in cognitive stability, as indicated by the conflict adaptation effect (for a review see Egner, 2007). This conflict-induced goal shielding comes at the cost of decreased flexibility, as indicated by greater task-switch costs (e.g., Brown, Reynolds, & Braver, 2007; Goschke, 2000) or impaired background monitoring for task-irrelevant, but potentially significant, stimuli (Goschke & Dreisbach; 2008). Moreover, Dreisbach and Goschke (2004) demonstrated that the induction of positive affect increases cognitive flexibility at the cost of cognitive stability. On the other hand, Müller, Dreisbach, Goschke, et al. (2007) showed that monetary rewards can increase cognitive stability at the cost of flexibility. These empirical findings indicate that there is a reciprocal relationship between cognitive stability and flexibility: High cognitive stability comes along with reduced cognitive flexibility, whereas high cognitive flexibility comes at the cost of reduced stability and increased distractibility (for a recent review see Dreisbach and Fröber, 2019). Considering the complementary costs and benefits of cognitive stability and flexibility, the question of how the balance between these control modes is dynamically achieved arises. Thus, how is control itself controlled? Research over the last few years has already identified situational and individual factors like affect, motivation, task context (for a recent review see Dreisbach & Fröber, 2019), genes, culture, nationality/ethnicity, religion and sexual orientation (for a recent review see Hommel & Colzato, 2017) that bias the cognitive systems toward cognitive stability or flexibility (see also Hommel, 2015). For instance, carriers of a polymorphism that increases prefrontal dopamine levels showed greater task switching costs than carriers of other polymorphisms (Colzato, Waszak, Nieuwenhuis, Posthuma, & Hommel, 2010). Moreover, an analytic processing style (as it is typical for individualistic cultures) is associated with a bias toward stability, whereas a holistic processing style (as it is typical for collective cultures) is associated with a bias toward flexibility (Hommel & Colzato, 2017). Religious disbelief and reduced religious practice are related to enhanced cognitive flexibility (cf. Zmigrod, Rentfrow, Zmigrod, & Robbins, 2019). Importantly, the balance between cognitive flexibility and stability is also modulated by affect and motivation (for reviews see Chiew & Braver, 2011; Dreisbach & Fischer, 2012; Dreisbach & Fröber, 2019; Goschke & Bolte, 2014). The present thesis builds upon this literature.

Cognitive stability and especially cognitive flexibility have been used to mean many different things in different contexts, thus it is important to clearly define cognitive stability and flexibility in the context of the present research. For instance, cognitive flexibility is a broadly used term, which can describe abilities ranging from creativity and higher verbal fluency to the flexible update of task relevant information. The present thesis investigated the influence of affect and reward motivation on cognitive control by using a context processing task (the AX-Continuous Performance Task, see below). Since the *Dual Mechanisms of Control* (DMC) framework by Braver (2012) is well suited to interpret variabilities in context processing tasks (Chiew & Braver, 2017), it is used to narrow the concepts of cognitive stability and flexibility.

The Dual Mechanisms of Control (DMC) Framework

In his DMC framework, Braver (2012) focuses on the timescale of implementation of cognitive control to differentiate between two complementary control modes: Proactive and reactive control (Braver, Gray, & Burgess, 2007). A proactive control strategy is engaged in anticipation of a conflict or cognitive demanding event and is defined by a strong maintenance of context or goal-relevant information, which leads to preparatory activity[3]. A reactive control strategy is engaged after the occurrence of a conflict and is defined as a 'just-in-time' control that has to be activated by an appropriate bottom-up stimulus trigger (Braver, 2012). Take, for example, the employee on his daily way to work who can use context information such as volume of traffic, road closures or construction sites to proactively adjust his driving style to the expected road conditions. Without such valid context information or without using such context information, the employee could get stuck in a traffic jam and has to flexibly change the route to work by activating reactive control (cf. Hefer & Dreisbach, 2016).

Proactive control is assumed to rely on the active maintenance of context representations in the lateral PFC. Reactive control, on the other hand, is associated with transient (rather than sustained) activation of lateral PFC after the onset of an imperative stimulus. This transient activity reflects the bottom-up reactivation of task goals after detection of a demanding event, which is assumed to be mediated additionally by posterior cortical regions or the hippocampal / medial temporal lobe complex and the ACC conflict monitoring system (Braver et al., 2007). Thus, the same lateral PFC regions implement different modes of cognitive control depending on the temporal dynamics of the activity (Braver, 2012; for empirical evidence see Braver, Paxton, Locke, & Barch, 2009). Additionally, the two control modes should differ in terms of the involvement of the dopamine (DA) system (cf. Chiew & Braver, 2017). DA is a neurotransmitter that is important for cognitive control function, reward and motivation (Botvinick & Braver, 2015).

[3] Please see Janowich and Cavanagh (2019) who dissociate between two subtypes of proactive control: 'goal-updating' and 'active maintenance' depending on temporal demands.

Advantages and disadvantages of proactive and reactive control

Similar to the concepts of stability and flexibility, proactive and reactive control strategies also have advantages and disadvantages (Braver et al., 2007). On the one hand, the continuous maintenance of task goals in an activated state (proactive control) allows for anticipatory behavior, which improves task performance and eventually facilitates goal achievement. However, such an anticipatory behavior requires the presence of highly predictive context cues, which to maintain is supposed to be metabolically costly. Therefore, proactive control should be preferentially engaged in situations with high motivational value or with the possibility of reward maximization. On the other hand, the rigid maintenance and usage of goal-relevant features also has its downsides: Because of reduced background monitoring, the system runs the risk of missing important information like changes in reward and punishment contingencies (Braver et al., 2007). Reactive control, by contrast, is a more bottom-up driven control strategy that is activated when either advance preparation is not possible, attentional resources are limited, or the motivation to put effort into performing a task is rather low. However, there are also noteworthy disadvantages: A reactive control strategy results in slower and less reliable performance than proactive control, because it requires the reactivation of task goals – a time-consuming process – which depends on sufficiently salient trigger events (Braver, 2012). Because both control strategies are associated with complementary costs and benefits, the cognitive system is likely to use both conjointly thereby taking advantages of both strategies and overcoming their restrictions (Braver et al., 2007). There is indeed empirical evidence that proactive and reactive control reflect independent mechanisms and thus can be recruited independently and even simultaneously (cf. Gonthier, Braver, & Bugg, 2016a; Mäki-Marttunen, Hagen, & Espeseth, 2019a).

Weighting between proactive and reactive control

First and foremost, the weighting between proactive and reactive control depends on participants' expectancies about the upcoming task. For example, when participants experience a high frequency of incongruent stimuli in a response conflict paradigm (e.g., many color words in non-matching ink colors in the Stroop task), they increase proactive control, resulting in overall reduced conflict interference (Bugg & Braver, 2016; Bugg & Crump, 2012; Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979). The contribution of proactive control also depends on the predictive validity of contextual information (Redick, 2014) and the salience of contextual cues (Lee & Park, 2006). Aside from expectancies, the contribution of proactive control depends on individual characteristics: Proactive control is reduced in patients suffering from schizophrenia (Cohen, Barch, Carter & Servan-Schreiber, 1999; Lesh et al., 2013), it is increased in bilingual individuals (Morales, Yudes, Gomez-Ariza, & Bajo, 2015), it declines with age (Braver et al., 2009; Braver, Satpute, Rush, Racine, & Barch, 2005), and it is positively correlated with intelligence and working memory capacity (Burgess & Braver, 2010; Redick, 2014; Wiemers & Redick, 2018). For instance, Speer, Jacoby, and Braver (2003) manipulated the expected memory load in a Sternberg item recognition task and showed that in the low-load condition participants implemented proactive control, whereas in the high-load condition they implemented reactive control. Speer and colleagues concluded that under high load conditions, a proactive control strategy was considered too difficult, and thus a reactive control strategy was preferred. This findings is consistent with research by Mäki-Marttunen, Hagen and Espeseth (2019b), who found increased reactive control under increased task context load. Training with a proactive control strategy can increase the engagement in proactive cue usage (Edwards, Barch, & Braver, 2009; Gonthier, Macnamara, Chow, Conway, & Braver, 2016b; Paxton, Barch, Storandt, & Braver, 2006), whereas the inclusion of no-go trials (in the AX-Continuous Performance Task, see below) can shift participants away from using proactive control (Gonthier et al., 2016b). Importantly for the present thesis, compelling evidence suggests that performance-contingent reward promotes context utilization and response preparation, which is a characteristic feature of proactive control (Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a; Jimura, Locke, & Braver, 2010; Locke & Braver, 2008; Mann, Footer, Chung, Driscoll, & Barch, 2013; Padmala & Pessoa, 2011; Strang & Pollak, 2014; Qiao et al., 2018; Yamaguchi & Nishimura, 2019). Positive affect and performance non-contingent reward, by contrast, are accompanied by reduced proactive control (Fröber & Dreisbach, 2012, 2014, 2016a; van Wouwe, Band, & Ridderinkhof, 2011) and/or increased reactive control (Dreisbach, 2006).

Specification of the terms "cognitive stability" and "cognitive flexibility"

As already mentioned above, the terms cognitive stability and flexibility are used to mean different things; thus, it is important to provide a precise definition for the purpose of the current investigations. Although the terms cognitive stability and proactive control do not describe identical concepts, they will both be used in this thesis to express *cue maintenance* and the *proactive usage of contextual information*. Cognitive flexibility is here defined as a consequence of *reduced context usage* allowing the *flexible adjustment to incoming task-*

relevant information (feedback from the environment). Thus, the present thesis focuses on reactive flexibility, or the readiness to shift behavior in reaction to external cues and changing situational demands (Eslinger & Grattan, 1993).

Following the precise specification of the control modes under investigation (dependent variables), the next section will precisely describe the independent variables, motivation and affect.

Motivation and Affect

Positive affect arises in various situations, for example when receiving a phone call from a very good friend or one's salary at the end of the month. Likewise, looking at the family picture on the office desk, receiving an unexpected gift, or having the door held open by a helpful person can all increase positive affect. The given examples describe situations that all result in a pleasant feeling. However, the source of this pleasant feeling is not always the same: Receiving an unexpected gift falls into the category 'performance non-contingent reward', whereas looking at a nice picture falls into the category 'positive stimuli', and receiving a monthly salary falls into the category 'performance-contingent reward'. There is growing evidence that the source of positive affect (positive stimuli vs. performance-(non)contingent reward, cf. Fröber & Dreisbach, 2014) plays a central role in determining how it affects cognitive processes. Therefore, to disentangle the impact of motivation and affect on cognitive control (and consequently to shed light on inconsistent findings in this research field), it is important to precisely specify these constructs (cf. Chiew & Braver, 2011). In the studies presented here, the focus was on the influence of *reward motivation* and *mild positive affect* (as a simple, nonreflecting feeling) on proactive cue usage.

Yee and Braver (2018) summarized that the "term 'motivation' is consistently used to describe when an external or internal incentive alters the biological system (i.e., generates a 'motivated state') to stimulate an observable change in behavior" (Yee & Braver, 2018, p. 83). Such motivated states can be induced by providing incentives, including both primary (e.g., food) and secondary (e.g., money) rewards or penalties. In the present thesis, reward incentives (participants had the chance to win money or points for fast and correct responses) were offered with the aim of producing a motivational state that would induce dynamic adjustments in cognitive processing, and consequently in behavioral performance (for a review on motivation-cognition interaction see Yee and Braver, 2018). When considering the effects of reward motivation on cognitive control, it is important to keep in mind that different components of reward may have different effects: Whereas reward prospect has motivational effects on cognition leading to preparatory activity by means of proactive control processes, reward reception has reinforcing effects leading to increased goal-relevant associations (for a review see Notebaert and Braem, 2015). Additionally, performance-contingent rewards, which increase proactive cue usage (e.g., Chiew & Braver, 2013, 2014) have different effects than performance non-contingent rewards, which decrease proactive cue usage (see Fröber & Dreisbach, 2014, 2016a). This topic will be discussed in more detail in the General Discussion. Important to mention at this point is that Studies 1 and 2 of the present thesis focus on the motivational effect of the prospect of performance-contingent reward on proactive cue usage. The rewards offered will be extrinsic, within participants' conscious awareness, and will have a constant high value.

Similar motivation, emotion is a nuanced concept, and there is not yet a clear consensus on the definition[4]. However, the main aim of the present thesis (especially of Study 3) was not to investigate the influence of a specific emotion on cognitive control, but of positive affect as the elementary affective experience of feeling good ("core affect", Russell, 1980). Russell (1980) describes affective experiences ("core affect") as a space formed by two bipolar, but independent dimensions, namely valence (varying from negative/unpleasant to positive/pleasant) and arousal (varying from low/deactivated to high/activated; Barrett & Russell, 1999). All affective experiences can be understood as combination of these two dimensions ("circumplex model", Russell, 1980). Thus, the circumplex model of affect is primarily a representation of the structure of core affect, which is defined as a "neurophysiological state that is consciously accessible as a simple, nonreflective feeling that is an integral blend of hedonic (pleasure-displeasure) and arousal (sleepy-activated) values" (Russell, 2003, p. 147). More simply spoken, core affect is "[…] what is commonly called a *feeling*" (Russell, 2003, p. 148). Russell describes core affect as analogous to felt body temperature in that it is always there and especially extremes (hot and cold) will be noted (Russell, 2003). In contrast to core affect, "an emotional episode is an event that counts as a member of an emotion category, such as that labeled *fear*" (Russell, 2003, p. 151). In other words, emotional episodes last a certain amount of time, are always directed at a specific object

[4] A common way to define emotions is by decomposing them into three components: Behavioral action (a motor output, such as crying or laughing), conscious experience (a subjective feeling), and physiological expression (autonomic activity, such as increased blood pressure, Purves et al., 2008).

(e.g., being afraid *of* something), and include an appraisal of and attribution to that object. So, it is core affect plus other specific components (such as "perception of affective quality" and "attributed affect", Russell, 2003, p. 150) that result in an emotional episode.

In accordance to this circumplex model of affect, Study 3 of the present thesis focuses on the influence of positive affect low in arousal on proactive cue usage.

Diverging Effects of Positive Affect and Reward Motivation on Cognitive Control

This section will introduce some empirical findings. To facilitate the comparison between previous findings and those of the present thesis, I will mainly focus on the influence of positive affect and reward motivation on cognitive control process. There is of course also research exploring the influence of negative affect (for a review see Bolte & Goschke, 2010) and punishment on cognitive control (cf. Braem, Duthoo, & Notebaert, 2013; Dambacher, Hübner, & Schlösser, 2011), but this is out of the scope of the present investigation.

To provide an overview, I will briefly review some general findings before going into more detail and reviewing studies that focus on proactive cue usage[5] and are thus most relevant to the present thesis.

Overview of the Motivational and Affective Modulation of Cognitive Control

Reward motivation and cognitive control

Performance-contingent reward enhances performance in a broad range of cognitive control processes including attention (e.g., Engelmann, Damaraju, Padmala, & Pessoa, 2009; Shomstein & Johnson, 2013), visual search (e.g., Navalpakkam, Koch, & Perona, 2009), memory (e.g., Miendlarzewska, Bavelier, & Schwartz, 2016), response inhibition (e.g., Boehler, Schevernels, Hopf, Stoppel, & Krebs, 2014), interference effects (e.g., Chiew & Braver, 2016; Padmala & Pessoa, 2011), conflict adaptation (e.g., Braem, Verguts, Roggeman, & Notebaert, 2012; Stürmer, Nigbur, Schacht, & Sommer, 2011), working memory (e.g., Heitz et al., 2008; Jimura et al., 2010), task switching (e.g., Kleinsorge & Rinkenauer, 2012;

[5] The first evidence for opposing effects of positive affect and reward motivation on cognitive control comes from studies investigating the conflict adaptation effect (for a review see Dreisbach & Fischer, 2012).

Umemoto & Holroyd, 2015), task-shielding (Fischer, Fröber, & Dreisbach, 2018), and – most importantly for the present thesis – *cue maintenance* (e.g., Chiew & Braver, 2013, 2014, Fröber & Dreisbach, 2014, 2016a; Locke & Braver, 2008; Qiao et al., 2018). Thus, reward is assumed to increase cognitive stability thereby improving task performance. But there is also research that does not fit in this general picture of reward-improved task performance (cf. Braver et al., 2014; Hefer & Dreisbach, 2016; for a review see Bonner et al., 2000).

Positive Affect and cognitive control

Positive affect, on the other hand, improves creative problem solving (e.g., Estrada, Young, & Isen, 1994) and verbal fluency (e.g., Phillips, Bull, Adams, & Fraser, 2002), reduces response conflict (e.g., Xue et al., 2013) and switch costs (e.g., Wang, Chen, & Yue, 2017; Yang & Yang, 2014), impairs working memory storage capacity (Martin & Kerns, 2011; but see Yang, Yang, & Isen, 2013), broadens the scope of attention (e.g., Rowe, Hirsh, & Anderson, 2007), promotes a focus on global rather than local perceptual features (e.g., Gasper & Clore, 2002), reduces task shielding in a dual task paradigm (Zwosta, Hommel, Goschke, & Fischer, 2013) and – importantly for the present thesis - *reduces cue maintenance* (e.g., Dreisbach, 2006; van Wouwe et al., 2011). These results indicate that positive affect increases cognitive flexibility which comes at the cost of increased distractibility (Dreisbach & Goschke, 2004)[6].

The Differential Influence of Positive Affect and Reward Motivation on Proactive Cue Usage

All studies reviewed below have used the AX-continuous performance task (AX-CPT; Servan-Schreiber, Cohen, & Steingard, 1996). This is a context processing task that allows researchers to measure the contribution of proactive and reactive control. Because this task was also applied in all studies presented here, it will now be introduced in more detail.

The AX-Continuous Performance Task (AX-CPT)

In the AX-CPT sequences of letters are presented. The first letter is called the cue, and the last letter is called the probe. Subjects have to respond to the probe. There are two types of cue (A or B), and two types of probe (X or Y), resulting in four different cue-probe conditions (AX,

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[6] But see Bruyneel et al. (2013), Chiew and Braver (2014) and Sacharin (2009) whose findings do not fit into this general picture.

AY, BX, and BY trials). The B-cue and Y-probe stand for any letter of the alphabet except for the letters A and X. If an A-cue is followed by an X-probe, a target response is required (AX target trials). If an A-cue is not followed by an X-probe (AY trials) or the cue is not an A (BX, BY trials), trials are called nontarget trials and require a nontarget response. Thus, only on AX target trials must participants give a target response (e.g., right key press), whereas on all other trial types they give a nontarget response (see Table 1). Crucially, in the standard AX-70 version of the AX-CPT, AX target trials occur with a frequency of 70%. All remaining nontarget trials occur with a frequency of 10% each. Consequently, the A-cue leads to a strong expectation of the X-probe (and the respective target response) because of its high frequency. In this case, increased proactive cue usage typically impairs performance on AY trials, as indexed by increased error rates and reaction times, because of the A-cue triggered target response activation. Decreased proactive cue usage (and increased reactive control) instead typically results in improved AY trial performance, because the lack of advance preparation means that no A-cue triggered response bias has to be overcome. Increased reactive control is accompanied by impaired performance on BX trials, as indexed by higher reaction times, because the X-probe triggered target response bias has to be overcome and episodic information about the context has to be retrieved from memory, both of which are time-consuming processes (for a corresponding argument see Chiew & Braver, 2017; Paxton et al., 2006; see Table 1). In addition to behavioral measurements, event-related brain potentials (ERPs; Chaillou, Giersch, Hoonakker, Capa, & Bonnefond, 2017; Morales et al., 2015; van Wouwe et al., 2011) and measures of pupil diltion (Chiew & Braver, 2013, 2014) can also serve as reliable indicators especially of proactive cue usage and have supported the involvement of proactive and reactive control in the AX-CPT.

Table 1. Assignment of cues and probes to correct response keys (upper table) and how to measure proactive and reactive control within the standard AX-70 version of the AX-CPT (lower table). AX trials require a target response (e.g., right key press), all other trials (AY, BX, BY) require a nontarget response (e.g., left key press).

Cue / Probe	**X**	**Y**
A	right key press AX target trials (70%)	left key press AY nontarget trials (10%)
B	left key press BX nontarget trials (10%)	left key press BY nontarget trials (10%)

Control mode	**Error Rate**	**Reaction Time**
Increased proactive control	AY > AX, BX, BY because the A-cue prepares the target response	AY > AX, BX, BY because the A-cue triggered target response bias has to be overcome
Increased reactive control	AY = BX = BY because no response is prepared in advance	BX > AY because the X-probe triggered target response bias has to be overcome

The modified version of the AX-Continuous Performance Task

Even though the AX-CPT is a well-validated task for investigating the involvement of proactive and reactive control, there is one critical objection against the AX-CPT: The cue allows for a response activation (target response after A-cue, nontarget response after the B-cue, see Table 1) that has to be overcome only in the rare case of an AY trial. That is, in the standard AX-CPT, participants could always prepare the target response after an A-cue was presented (thereby accepting errors on AY trials) and the nontarget response after a B-cue. Applying this simple strategy would result in perfect and very fast performance on AX, BX, and BY trials and high error rates on AY trials. To avoid the usage of such a purely cue-driven strategy, the standard AX-CPT must be modified such that the cue no longer allows for response preparation but rather for rule preparation only. In a first study, we therefore developed a modified version of the AX-CPT (Hefer & Dreisbach, 2016): In this modified version, the combination of cue and number of probes determines the correct response rule. Specifically, the cue A or B is followed by one or two probes (X/XX or Y/YY). Comparable to the standard version of the AX-CPT, frequent AX target trials require a target response rule (e.g., one X-probe – down arrow key, two XX-probes – up arrow key). Infrequent nontarget trials require the reversed nontarget response rule (e.g., one probe – up arrow key, two probes – down arrow key; see Table 2). In the so-called AX-70 version, AX and AXX trials occur with a frequency of 35% each. AY/BX/BY and AYY/BXX/BYY trials occur with a frequency of 5% each. The terms AX, AY, BX and BY trials always refer to both AX and AXX, AY and AYY, BX and BXX, and BY and BYY trials respectively, because of main interest was the distinction between target (AX) vs. nontarget (AY, BX, BY) trials, rather than between conditions in which one or two probes appeared. In sum, the modified version of the AX-CPT no longer allows for advance response preparation, but only for *rule* preparation. Consequently, it is no longer possible to apply a purely cue-driven strategy, which makes the modified AX-CPT more sensitive to shifts toward or away from cognitive stability, and to the efficient use of both proactive and reactive control. Basically, the level of proactive cue usage can be assessed by the proportion of AY errors relative to BX errors as well as by the comparison of AY RTs relative to BX RTs (Chiew & Braver, 2017; Doebel et al., 2017). Increased cognitive stability results in a cue-triggered interference effect whenever the A-cue is not followed by the expected X-probe(s) but by the unexpected Y-probe(s). To keep AY errors to a minimum reactive control has then to be activated to overcome the proactively prepared but inappropriate response rule. Thus, reactive control prevents errors on AY trials because of expectancy violations but is a time-consuming process. That is, increased AY RTs (compared to BX RTs) along with low AY errors (comparable AY and BX errors) are a sign of the efficient use of both proactive *and* reactive control (cf. Hefer & Dreisbach, 2016). Whenever participants rely solely on proactive control (which is the case, for example, in the context of performance-contingent reward) without activating reactive control when needed, both RTs and error rates on AY trials should be higher compared with RTs and error rates on BX trials.

Table 2. Assignment of cues and probes to correct response keys (upper table) and how to measure proactive and reactive control within the modified AX-CPT (lower table). Comparable to the standard AX-CPT, AX trials require a target response rule, in all other trials (AY, BX, BY) this rule reversed.

Cue / Probe	**X**	**XX**	**Y**	**YY**
A	down arrow key	up arrow key	up arrow key	down arrow key
	AX target trials (70%)		AY nontarget trials (10%)	
B	up arrow key	down arrow key	up arrow key	down arrow key
	BX nontarget trials (10%)		BY nontarget trials (10%)	

Control mode	**Error Rates**	**Reaction Time**
Efficient reliance on proactive and reactive control	AY = BX because reactive control helps to overcome the proactively prepared but inappropriate target response rule in AY trials	AY > BX because overcoming an already prepared response rule is a time-consuming process
Increased proactive control	AY > BX because the A-cue prepares the target response rule	AY > BX because the A-cue triggered target rule bias has to be overcome
Increased reactive control	AY = BX because no response rule is prepared in advance	AY < BX because the X-probe triggered target rule bias has to be overcome

The influence of reward motivation on proactive cue usage

To the best of my knowledge, all studies that investigated the influence of performance-contingent reward on proactive cue usage found increased error rates on AY trials (Chaillou et al., 2017; Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a; Jimura et al., 2010; Locke & Braver, 2008; Mann et al., 2013; Strang & Pollak, 2014). This finding is very robust and replicates across various research designs. As already mentioned above, one critical objection against the AX-CPT is that in the more commonly used standard version, participants can rely purely on a cue-driven strategy. Therefore, the question arose about whether the often-replicated reward effect of increased cue maintenance goes beyond a mere response preparation. To answer this question, Hefer and Dreisbach (2016) used the modified version of the AX-CPT (see above) and compared the performance of a neutral group with a group that received performance-contingent reward for fast and correct responses in miniblocks of 20 trials. The study found higher error rates on AY trials in the reward group compared with the neutral group thus confirming a sustained shift toward proactive cue usage. That is, the well-documented reward effect is not limited to mere response preparation but can also be found when the cue allows only for rule preparation (Hefer & Dreisbach, 2016, Experiment 1). In a second experiment, we went one step further, and aimed to investigate whether the interaction of reward-induced motivation and proactive cue usage is limited to necessary cue information (see Sudevan and Taylor, 1987, for an explanation of the differentiation between cue and prime information). To this end, in Experiment 2, the modified AX-CPT was used with a modified response mapping such that the cue was no longer necessary because the X-probe required a X-rule and the Y-probe required a Y-rule irrespective of the preceding cue (A or B). Nevertheless, the reward group still used the A-prime to prepare the X-rule. Taken together, the results of this study demonstrate that the reward-induced increase in proactive cue usage is very strong and goes beyond mere response preparation and cues that are necessary as advanced context information. This second finding is especially intriguing considering that the introduction of reward did not result in an overall improvement of task performance (which is in contrast to findings by Chiew and Braver, 2013, 2014 as well as Fröber and Dreisbach, 2014). A key question concerns why rewarded participants used priming information to prepare a response rule at the cost of higher error rates, even though this information was not necessary to accomplish the task. One explanation might be that reward incentives not only increased cognitive stability in terms of proactive cue usage but also decreased cognitive flexibility in terms of reduced ability to adapt behavior to error feedback. This research question, derived from the study by Hefer and Dreisbach (2016), served as a starting point for **Studies 1 and 2** of the present thesis.

The influence of positive affect on proactive cue usage

In contrast to reward prospect, positive affect reduces top-down control as evidenced by decreased cue usage (Chaillou et al., 2018; Dreisbach, 2006; Fröber & Dreisbach, 2012; van Wouwe et al., 2011). In the cited studies, affect was manipulated with affective pictures (positive, neutral or negative) from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1999) preceding every trial (Dreisbach, 2006; Fröber & Dreisbach, 2014), with positive and neutral IAPS pictures presented randomly intermixed preceding every trial (Chaillou et al., 2018; Chiew & Braver, 2014), and/or with emotional film clips (positive or neutral) prior to the experiment (Chiew & Braver 2014; van Wouwe et al., 2011). Compared with neutral (and negative) affect, positive affect reduced error rates in AY trials (Dreisbach, 2006; Fröber & Dreisbach, 2014; van Wouwe et al., 2011), and increased error rates in BX trials (Dreisbach, 2006)[7] suggesting a shift toward decreased cue usage.

There are two noteworthy studies, that directly compared the influence of positive affect and reward prospect on cognitive control (Chiew & Braver, 2014; Fröber & Dreisbach, 2014). Chiew and Braver (2014) used a within-subject design: Participants performed the standard AX-CPT under both emotion and motivation conditions in separate sessions with counterbalanced order. The emotional session started with a neutral baseline block with neutral IAPS pictures on each trial followed by a positive block with 50% neutral and 50% positive IAPS pictures randomly intermixed. The motivation session started with a neutral baseline block followed by a reward block with 50% rewarded trials. In this session neutral IAPS pictures were presented on all trials. Right before each neutral baseline block and the reward block, participants viewed a neutral video, whereas before the positive block they viewed a positive video. The authors replicated the results of their study from 2013: Reward effects were found in block- and trial-based contrasts, improving performance in all trials except in AY trials, which supports the idea that reward increases proactive usage of contextual information. This finding is in line with Fröber and Dreisbach (2014) who used a between-subject design. In a first step, they manipulated affect using either neutral vs. positive IAPS

[7] Note, that the positive affect effect might be more susceptible to subtle differences in research designs compared with the reward effect. Different results regarding the influence of positive affect on BX performance, might be due to different feedback procedures (for more information see Fröber and Dreisbach, 2014).

pictures preceding every trial. In a second step to manipulate motivation, the affect groups were split and received either performance-contingent or performance non-contingent (random) reward on 50% of the trials. This method resulted in a completely orthogonal design with four groups: NeutralReward, PositiveReward, NeutralRandomReward, and PositiveRandomReward. In the first phase of the experiment, in which affect was manipulated, the authors showed reduced AY errors in the positive affect group compared with the neutral affect group, suggesting decreased cue maintenance under positive affect. Of special interest in this study was the interaction of positive affect and performance-(non)contingent reward, which was manipulated in the second phase of the experiment. They found that the motivational effect of performance-contingent reward trumped the positive affect effect from the the first phase of the experiment, as evidenced by a reward-induced increase in AY errors in the NeutralReward *and* PositiveReward group. Thus, motivational influences overcome affective influences (see also Walsh, Carmel, & Grimshaw, 2019). Additionally, the effect of performance non-contingent reward mirrored performance under positive affect: Adding random reward was accompanied by a reduction in AY errors in the NeutralRandomReward group, indicating a shift toward reduced cue usage (see also Fröber & Dreisbach, 2016a). Interestingly, the positive affect-related findings of Fröber and Deisbach (2014), who found performance *benefts* on AY trials, contrasts with those of Chiew and Braver (2014), who found performance *costs* on AY trials. Thus, even though the positive affect effect was found in several studies, the opposing findings by Chiew and Braver (2014) cast doubt about the reliability of the positive affect effect (see also Chaillou et al., 2018, whose finding of impaired cue usage under positive affect was mainly based on analyses of event-related potentials). The aim of **Study 3** was to explore whether time on task might be a further moderator variable, like motivation as shown in Fröber and Dreisbach (2014), which might have caused these contradictory findings.

Summary and Current Research

Taken together, studies investigating cognitive stability vs. flexibility in terms of increased vs. decreased proactive cue usage found opposing effects for performance-contingent reward, performance non-contingent reward, and positive affect (Chiew & Braver, 2013; Dreisbach, 2006; Fröber & Dreisbach, 2012, 2014, 2016a; Jimura et al., 2010; Locke & Braver, 2008; Qiao et al., 2018; van Wouwe et al., 2011). It thus seems that performance-contingent reward increases cue usage in the AX-CPT, whereas positive affect and performance non-contingent reward decreases cue usage in the AX-CPT. Even though recent research has started to disentangle the differential influence of positive affect induced by performance-contingent reward, performance non-contingent reward and positive pictures, there are still unanswered questions: How can diverging findings by Chiew and Braver (2014), who found increased cue usage under positive affect, and Fröber and Dreisbach (2014), who decreased cue usage under positive affect, be explained? How can reward-induced performance improvements (Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a) vs. performance impairments (Hefer & Dreisbach, 2016) be explained? Could it be that reward prospect increases cognitive stability at the cost of decreased flexibility (cf. Müller et al., 2007), in essence having the opposite effect to positive affect, which increases flexibility at the cost of increased distractibility (cf. Dreisbach & Goschke, 2004)? The following three studies addressed these questions.

Study 1 extended research on how reward motivation modulates the balance between stability and flexibility and – more specifically – clarified whether reward-induced increases in cognitive stability come at the cost of decreased flexibility.

Study 2 is a direct follow-up study and explored in more depth the mechanism underlying the reward-induced maladaptive and perseverative cue usage found in Study 1.

Study 3 investigated the vulnerability of the positive affect effect in order to shed lights on inconsistent findings in this research field.

All studies presented here used the AX-CPT, for several reasons. Using the AX-CPT allowed for replication and extension of previous work (especially research by Chiew & Braver, 2014; Fröber & Dreisbach, 2014, 2016a; Hefer & Dreisbach, 2016) and to maintain comparability between similar studies. Moreover, the AX-CPT (especially in its modified version) is very sensitive to the engagement of proactive cue usage in the context of performance-contingent reward prospect. Of importance to the present research, the systematic manipulation of the predictive value of the cueing information allows for the manipulation of the efficiency of a proactive control strategy.

PART II

PEER-REVIEWED STUDIES

STUDY 1

How performance-contingent reward prospect modulates cognitive control: Increased cue maintenance at the cost of decreased flexibility

Carmen Hefer and Gesine Dreisbach

Hefer, C., & Dreisbach, G. (2017). How performance-contingent reward prospect modulates cognitive control: Increased cue maintenance at the cost of decreased flexibility. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(10), 1643.

Abstract

Growing evidence suggests that reward prospect promotes cognitive stability in terms of increased context or cue maintenance. In three Experiments, using different versions of the AX-continuous performance task, we investigated whether this reward effect comes at the cost of decreased cognitive flexibility. Experiment 1A shows that the reward induced increase of cue maintenance perseverates even when reward is no longer available. Experiment 1B shows that this reward effect not only survives the withdrawal of reward but also delays the adaptation to changed task conditions that make cue usage maladaptive. And finally in Experiment 1C, it is shown that this reduced flexibility to adapt is observed in a more demanding modified version of the AX-CPT and is even stronger under conditions of sustained reward. Taken together, all three Experiments thus speak to the idea that the prospect of reward increases cue maintenance and thereby cognitive stability. This increased cognitive stability however comes at the cost of decreased flexibility in terms of delayed adaptation to new reward and task conditions.

Keywords: Stability, Flexibility, Performance-contingent Reward, AX-Continuous-Performance Task

Supplemental materials: http://dx.doi.org/10.1037/xlm0000397.supp

Introduction

A remarkable ability of the human cognitive system is to coordinate and adjust thoughts and actions in accordance with internally maintained goals. Such cognitive control is particularly necessary when goals or context-relevant information have to be maintained over time (stability) in the face of distraction or when goals and behavioral dispositions have to be switched (flexibility) in response to significant changes. Since stability and flexibility are antagonistic control demands (e.g. Dreisbach & Goschke, 2004; Hommel, 2015), the question arises how the balance between both is modulated. Growing evidence suggests that emotion and motivation each have a distinct influence on the stability-flexibility balance (for a recent review see Goschke & Bolte, 2014). For example, positive affect seems to increase flexibility at the cost of reduced stability (Dreisbach & Goschke, 2004; Dreisbach, 2006; Fröber & Dreisbach, 2012). On the other side, reward induced increases in motivation seem to promote goal maintenance and stability (Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a; Hefer & Dreisbach, 2016; Locke & Braver, 2008). Here we aim to investigate whether this increased stability under reward prospect comes at the cost of decreased flexibility (cf. Müller et al., 2007).

A large body of literature exists investigating the motivational and affective modulation of the balance between cognitive flexibility and stability (see Goschke & Bolte, 2014, for a recent review). For example, Dreisbach and Goschke (2004) used an attentional set-shifting paradigm to show that positive affect induced via short presentation of affective picture stimuli increases flexibility at the cost of increased distractibility (see also Fröber & Dreisbach, 2012; Liu & Wang, 2014). Likewise Dreisbach (2006) and Van Wouwe, Band, and Ridderinkhof (2011) observed reduced stability (i.e., context maintenance) under positive affect conditions. Fröber and Dreisbach (2014) replicated this positive affect effect and additionally showed that performance non-contingent reward has comparable effects (see also Fröber & Dreisbach, 2016a). Crucially for the study presented here, there exists much evidence that the prospect of performance contingent reward shows the reversed effect in terms of *increased* goal maintenance and stability (Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014; 2016a; Hefer & Dreisbach, 2016; Locke & Braver, 2008; Mann, Footer, Chung, Driscoll, & Barch, 2013; Padmala & Pessoa, 2011; Strang & Pollak, 2014). It should be noted that here and in the studies cited above, the focus was on the effects of reward *prospect* on cognitive control and not reward reception. While reward prospect has motivational effects on cognition, reward reception might rather have reinforcing effects and promote associative learning (for a recent review, Notebaert & Braem, 2015). Moreover, recent evidence suggests that the stability inducing effect found under reward prospect only holds for unchanged high reward amounts. When reward prospect changes from one trial to the next (increases or decrease), increased flexibility can be observed (Shen & Chun, 2011; Fröber & Dreisbach, 2016b; Kleinsorge & Rinkenauer, 2012). Here, we will again focus on the effects of (unchanged) reward prospect on cognitive stability.

So far there is no study directly examining the possible downside of such a reward induced increase of cognitive stability. Derived from the general framework that cognitive stability and flexibility are antagonistic control modes in nature coming along with qualitatively different costs and benefits (Goschke & Bolte, 2014; Hommel, 2015), we should be able to show that the prospect of reward goes along with reduced cognitive flexibility. Here, we aim to close this empirical gap by investigating whether the increased stability and context maintenance under reward conditions comes at the cost of decreased flexibility in terms of a delayed adjustment to changing reward and task conditions.

Reward and the AX-Continuous Performance Task

Most of the aforementioned studies investigating the influence of reward cognitive control used the AX-Continuous Performance Task (AX-CPT) (Servan-Schreiber, Cohen & Steingard, 1996), which we will now describe in detail. The AX-CPT is a well proven context-processing paradigm that is sensitive to shifts in context maintenance and stability. Several letters are presented sequentially. The first letter represents the "cue", the last letter the "probe". Participants have to maintain the cue in order to be able to give an answer to the then following probe. The probe requires – depending on the preceding cue - a target or non-target response. The target-response is required whenever the probe X follows the cue A. If the X-probe follows another letter (e.g. B) or the A-cue is followed by another letter than X (e.g., Y) or the cue is not an A and the probe is not an X, the non-target response key has to be pressed. In total, there are thus four different trial-types: AX target-trials, and AY, BX, and BY non-target trials. B and Y represent any letter from the alphabet except for A and X. Critically, AX sequences occur with 70% frequency, the non-target trials with 10% frequency each. Due to this frequency distribution, the A-cue produces a strong expectancy for the X-probe. And this expectancy leads to impaired performance especially on AY trials (higher error rate and slower RTs) when the A-cue is strongly maintained and used for the preparation of the X-probe. Hence, the stronger the A-cue is maintained (= stability), the higher the costs if this expectation is hurt (A-cue is followed by a Y-probe). At the same time, increased cue usage results in better performance on BX and BY trials because the B-cue unambiguously predicts a non-target response. Conversely, decreased cue maintenance leads to improved performance on AY trials because no cue-triggered target response bias has to be overcome.

To our knowledge, all studies using the AX-CPT found increased cue usage under (performance contingent) reward prospect as compared to a neutral control block, indicated by highly increased error rates on AY trials and decreased error rates and RTs on B-cue trials (Fröber & Dreisbach, 2014, 2016a; Chiew & Braver, 2013, 2014; Locke & Braver, 2008). Moreover, these studies examined transient (by comparing non-reward and reward trials/mini-blocks *within* a given block of potential reward) and sustained reward effects (by comparing non-reward trials *between* blocks without reward and blocks with potential reward). However, so far, there is no study that directly investigated the possible downside-effects of reward in terms of decreased flexibility to adjust to changing reward and/or task conditions.

To foreshadow, in a first experiment we replicated the typical reward effect in terms of increased cue usage within the AX-CPT. The results will also provide a first hint for reduced flexibility under reward because the reward induced stable cue usage perseverated even when reward was no longer available in a following non-reward block. These results were then taken as a starting point for two further experiments where we investigated more directly the assumed reduced cognitive flexibility under reward conditions.

Experiment 1A

Method

Participants. A total of 22 undergraduate students from the University of Regensburg participated for course credit. Two participants had to be excluded because of incomplete data due to technical problems. Thus, 20 participants were included in the final data analysis (16 female, 4 male, mean age = 21.5 years, *SD* = 3.3, range 18 - 34). Participants had no prior knowledge about reward availability. All participants signed informed consent and were debriefed after the session. All procedures performed in our studies were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Apparatus. Participants were tested individually in a lab at the University of Regensburg. The experiment was run on a Dell PC computer with a 17-inch monitor. The viewing distance was approximately 50cm. The experiment was presented using E-Prime 2.0 (Psychology Software Tools, Sharpsburg, PA, USA). Responses were collected using a QWERTZ keyboard, with the “y” and “m” keys serving as target and non-target response keys. The response mapping of the target and non-target responses was counterbalanced across participants.

Material and procedure. Participants worked through the same AX-CPT task already used in previous studies (Fröber & Dreisbach, 2014, 2016a). Each trial of the AX-CPT consisted of a sequence of letters. The letter A served as cue on AX and AY trials. The letter X served as a probe on AX and BX trials. Target trials (AX) were mapped to one response key, non-target trials (AY, BX, BY) to another response key. In between cue and probe, distractor letters were presented. B-cues, Y-probes and distractor letters were chosen randomly from the alphabet (beside A and X) without replacement. Cue and probe were presented in magenta (Arial font, bold, size 28), distractor letters were presented in black (Arial font, bold, size 24). All letters were presented centered on a gray background. Participants were instructed to ignore the black distractor letters because only the colored cue and probe letters were important to accomplish the task.

Ten different pictures of 5€ banknotes served as reward cues in Block 1 and Block 3 (see the Appendix A for an example of a banknote picture). In Block 2 ten different neutral pictures of the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1999) were used to make the trial structure comparable to the reward blocks (see the Appendix B for the numbers of the specific IAPS pictures). The mean ratings for the neutral picture set were valence = 4.99 and arousal = 2.45[8]. All pictures (neutral and banknote) were presented centered on a gray background in a landscape format, adjusted to a size of 800 x 600 pixel. Picture repetitions were not allowed on consecutive trials.

The trial structure is shown in Figure 1. Each trial began with the presentation of a neutral (in Block 2) or a banknote picture (in Block 1 and 3) for 400 ms which was followed by a blank screen for 100 ms. The cue appeared for 300 ms, followed by a blank screen (200 ms) and three distractor letters (each for 300 ms). After another blank screen (200 ms), the probe was presented and remained on the screen until a response was given. Responses were followed by a visual feedback message for 1500 ms. In the baseline block and the non-reward Block 2, the German word "Richtig!" ("Correct") in blue was presented after correct responses, the German word "Falsch!" ("Wrong") appeared in red as feedback message after an error was made. In the reward blocks 1 and 3 instead, feedback messages were changed to the German sentence "Richtig! Punkt erhalten" ("Correct! Point won") in green for correct responses below the RT cutoff,[9] "Zu langsam. Kein Punkt" ("Too slow. No point") in blue for correct but too

[8] Rating of IAPS pictures range between 9 (high pleasure, high arousal) and 1 (low pleasure, low arousal).

[9] i.e. within a RT threshold that was calculated for each cue-probe condition (AX, AY, BX and BY) and each individual participant as the fastest 30th percentile of correct baseline block reaction time. The probe still stayed

slow responses, and “Falsch! Kein Punkt” (“Wrong. No point”) in red for errors. Before the next trial an inter-trial interval (blank screen) of 500 ms was presented.

Participants had to give a target response on AX sequences, all other trial types (AY, BX, BY) required a non-target response. AX sequences occurred with 70% frequency and were randomly intermixed with the non-target trial types that occurred with 10% frequency each. Participants were informed that the cue would be presented only for a short time and that they had to react to the probe only.

The experiment started with written instructions and one practice block of 20 trials (14 AX, 2 AY, 2 BX and 2 BY, randomly intermixed) that enabled participants to become familiar with the AX-CPT. A baseline block of 80 trials (without picture presentation) was presented (80 trials; 56 AX, 8 AY, 8 BX, 8 BY) to determine the individual RT cutoff. Participants were not informed about this procedure to prevent a strategic slowing of responses in this baseline block. Participants then received three experimental blocks with a reward manipulation in Block 1 (160 trials; 112 AX, 16 AY, 16 BX, 16 BY) and Block 3 (80 trials; 56 AX, 8 AY, 8 BX, 8 BY)[10] only. There was no reward manipulation in Block 2 (160 trials; 112 AX, 16 AY, 16 BX, 16 BY). Participants had no a priori knowledge about reward availability but were only informed right before blocks 1 and 3. They were told that they could win one point on each trial for fast and correct responses in the following block. Furthermore, as an additional incentive, participants were informed that the three best of all participants would receive one cinema coupon each. Before Block 2 participants were informed that they would not receive any rewards in this block indicated by neutral pictures. Before each block, participants were asked to react as quickly and accurately as possible. A separate feedback message informed them about their point score after the first reward block and at the end of the experiment.

Data analysis and Design. For the analysis of performance data, practice trials and the first trial of each experimental block were excluded. In addition, error trials were excluded prior to the mean median RT analyses.

To investigate the reward effect and how flexibly it can be deactivated and reactivated, we analyzed changes in the behavioral performance between blocks (c.f. Fröber & Dreisbach, 2014; Chiew & Braver, 2013, 2014; Locke & Braver, 2008; Padmala & Pessoa, 2011). To this end, a 3 (cue-probe condition: AX, AY, BX) x 4 (block: baseline, block 1, 2 and 3) repeated

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on screen until a response was given (also beyond the RT cutoff, in which case a respective error message followed the response).

[10] The decision for a shorter Block 3 was driven by the concern that participants might otherwise loose interest in the task.

measures design was used for error rate (in %) analysis. BY trials had to be excluded because participants made no errors on BY trials in Block 3. Consequently, a 4 (cue-probe condition: AX, AY, BX, BY) x 4 (block: baseline, block 1, 2 and 3) repeated measures design was used for the analysis of reaction times (RTs, in milliseconds). We concentrated on the comparison of AY trials between blocks because it provides information about the level of cue maintenance: higher error rates *selectively* in AY trials are a sign for strong A-cue maintenance. A more detailed analysis of error rates and RTs can be found in the Supplementary Materials.

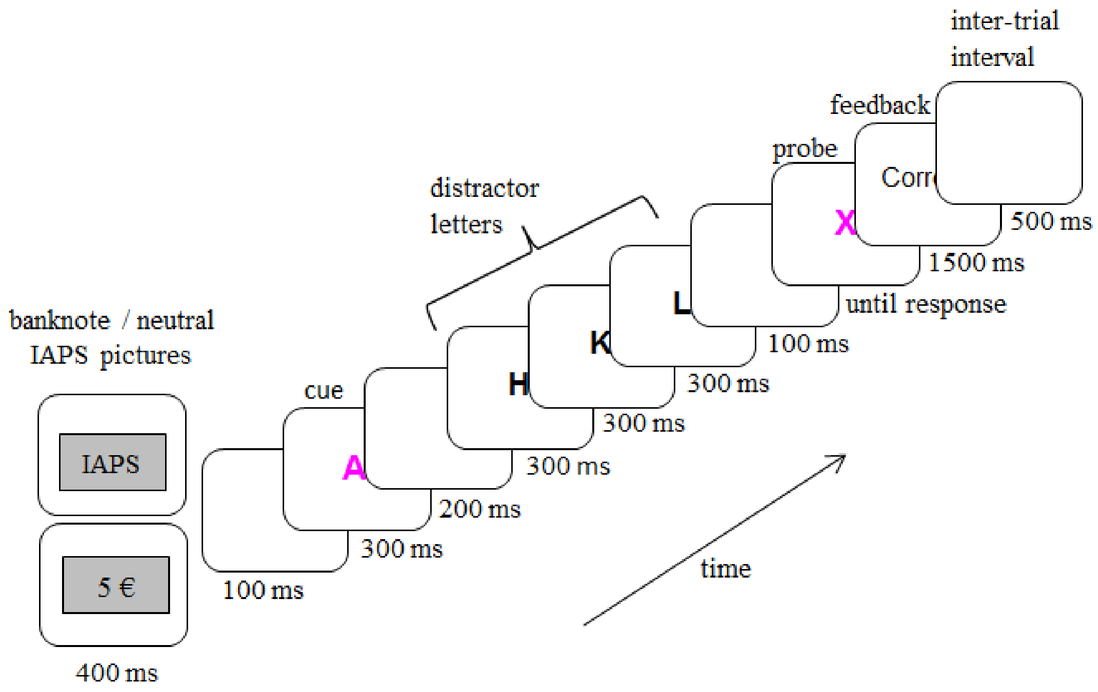


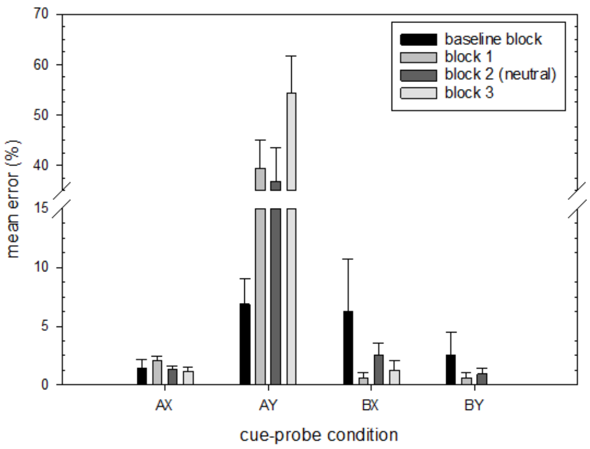
Figure 1. AX-continuous performance task trial structure. In the reward Blocks 1 and 3, a picture of a 5-Euro banknote was presented before every trial and served as reward cue. In the nonreward Block 2, a neutral International Affective Picture System picture replaced the picture of the banknote.

Results

Error rate. Error rates were entered into a 3 (cue-probe condition: AX, AY, BX) x 4 (block: baseline, block 1, 2 and 3) factors ANOVA (see Figure 2). All effects reached significance (all *F*s > 11.24, all *p*s < .001). Most importantly for our hypothesis the two-way interaction Cue-probe Condition x Block reached significance, $F(6, 114) = 24.38$, $p < .001$, $\eta_p^2 = .56$. In accordance with our hypothesis, planned comparisons showed significantly increased error rates selectively on AY trials in Block 1 as compared to the baseline block ($F(1, 19) = 38.75$, *p*

< .001, 6.9% vs. 39.4%), suggesting a shift towards increased cue maintenance in the reward context. Interestingly there was no significant difference on AY trials between Block 1 and the nonreward Block 2 (p = .6, 39.4% vs. 36.9%) but a significant further increase in AY error rate from Block 2 to Block 3, $F(1, 19) = 13.47$, $p < .01$, 36.9% vs. 54.4%.

RT data. RTs were entered into a 4 (cue-probe condition: AX, AY, BX, BY) x 4 (block: baseline, block 1, 2 and 3) factors design[11]. All effects reached significance (all Fs > 8.89, all ps < .001). Most importantly, the main effects were qualified by a significant interaction of Block x Cue-Probe Condition, $F(9, 144) = 8.89$, $p < .001$, $\eta_p^2 = .36$. Follow up planned comparisons regarding performance differences from the baseline block to the first reward block showed significantly faster RTs in the first reward block in all four cue-probe conditions (all Fs > 23.4, all ps < .001). In the nonreward Block 2 – without a RT threshold – a significant increase in RTs from Block 1 to Block 2 in AX and AY trials was observed (both Fs > 8.35, both ps < .01). From Block 2 to Block 3 a further significant decrease in RTs on all four cue-probe conditions was observed (all Fs > 9.97, all ps < .006) (see Figure 2).



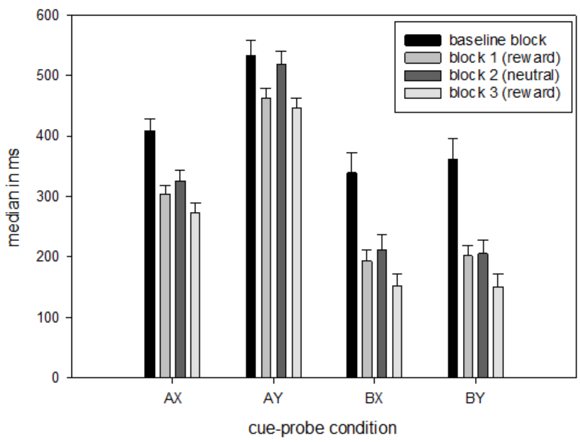


Figure 2. Experiment 1A: Mean error rates (left panel) and reaction times (right panel) as a function of cue-probe condition and block. Error bars represent one standard error of the mean.

Discussion

In Experiment 1A reward was manipulated between blocks. The data pattern presented here closely replicated those of previous studies and confirmed the typical reward effect in terms of

[11] Only 17of 20 participants were included in the RT analysis because three participants had an error rate of 100% on AY trials (one participant in Block 2 and 3, two participants in Block 3 only) (cf. Fröber & Dreisbach, 2014).

general performance benefits but specific error costs on AY trials, relative to baseline (cf. Fröber & Dreisbach, 2014, 2016a; Chiew & Braver, 2013, 2014). Even though RTs on AY trials increased in the non-reward Block 2, error rates remained on the high level of the first reward block. In Block 3, when reward was again available, participants showed signs of even more cue maintenance as evidenced by a further increase in error rates on AY trials. Moreover, the data pattern in RTs supports our assumption of robustly increased cue maintenance under reward conditions: a speeding-up in all cue-probe conditions from the baseline to Block 1 and from the non-reward Block 2 to Block 3 was observed. As mentioned above, in the non-reward block RTs of A-cue trials (but not of B-cue trials) significantly increased – not surprisingly as participants were no longer forced to reach the individual RT threshold. However, the unchanged high error rate on AY trials in the non-reward Block 2 provide a first hint for the persistent nature of reward induced cue maintenance. This is in line with Braver et al. (2007) arguing that cue maintenance is less sensitive to changes in reward contingencies. To sum up, the reward induced cognitive stability led to more perseverative behavior.

However, we should not draw premature conclusions from here because results might be evoked by the mere structure of the AX-task. That is, highly informative and useful context cues in the AX-CPT as well as a short retention interval between cue and probe made the maintenance and usage of cues a highly efficient and rewarding strategy by itself. In fact, Paxton, Barch, Storandt, and Braver (2006) observed increased AY errors as a time-on-task effect even a under neutral affect conditions. This is in line with recent research from our laboratory also demonstrating an increase in cue maintenance as a mere time on task effect even without any reward manipulation which however was only half the size compared to the reward effect presented here (Hefer & Dreisbach, 2018[12]). Moreover, the executive load of cue usage in the AX-CPT may be rather small. Therefore, a once increased cue maintenance (induced by reward) may be kept on a constantly high level even when reward is no longer available due to its task-inherent efficiency.

Therefore, in Experiment 1B, we reduced the efficiency of maintaining and using context information. That is, not only was reward taken back in Block 2 (as in Experiment 1A).

[12] In that study, we observed a significant increase of AY error rates from the first to the second block without any manipulation ($F(1, 19) = 5.94$, $p < .05$, 13% vs. 21%). Admittedly, this neutral group was part of another study and is not ideally suited as a neutral control condition for the present study because in that group we had no baseline block included. Still, the fact that participants of the study presented here, made almost twice as much errors on AY trials - even in the non-reward block 2 (37%) - relative to that neutral group in our former study suggests that performance in the non-reward Block 2 is not a mere time on task effect.

We additionally changed the frequency of the trial types such that cue usage was no longer advantageous: In Block 2, the A-cue was now followed by an X-probe and Y-probe with equal probability (AX-40%, AY-40%, BX-10%, BY-10%; hereafter we will refer to AX-70 and AX-40, see Redick, 2014). Thus, a stable cognitive control mode in terms of maintaining the A-cue and preparing an advance target-response based on the A-cue was adaptive in the AX-70 blocks but would become counterproductive in the AX-40 block. Consequently, for successful task performance in the AX-40 block participants should reduce their level of cue usage and no longer prepare the target response whenever the A-cue appears (see also Redick, 2014; Richmond, Redick, & Braver, 2015). We predict that the reward group (reward availability in the AX-70 block only) will be less flexible to adapt their level of cue maintenance in the following non-reward AX-40 block as compared to a neutral control group.

Experiment 1B

Aim of Experiment 1B was to test more directly whether reward prospect leads to perseverative cue maintenance at the cost of decreased flexibility. To this end, reward availability was not only eliminated in Block 2 but the proportion of AX and AY trials was changed as well to render cue usage less efficient. The A-cue was no longer informative because it was followed by a Y-probe (AY – 40%) and X-probe (AX – 40%) with the same probability. Due to this modification, a reduced level of cue maintenance on A-cue trials would be more advantageous in the AX-40 block than a perseverative high level (Redick, 2014). The predictive validity of the B-cue was unchanged, BX and BY trials occurred with a frequency of 10% each in both blocks. This time, we included a neutral control group as a standard for comparison. We expected increased cue maintenance in the reward group as compared to the neutral group in the AX-70 block (reward availability in the reward group) *and* in the AX-40 block (no reward availability). This would be interpreted as a sign of decreased flexibility as a downside-effect of the reward induced cognitive stability.

Method

Participants. A total of 40 undergraduate students from the University of Regensburg participated for course credit. All participants were included in the final data analysis (26 female, 14 male, mean age = 22.4 years, *SD* = 5.2, range 18 - 46). 20 participants were assigned to the reward and neutral group, respectively. Participants had no prior knowledge about reward availability. All participants signed informed consent and were debriefed after the session.

Apparatus. The apparatus was identical to Experiment 1A.

Material and procedure. The material and procedure were comparable to those in Experiment 1A with only a few exceptions that will be described in the following. This time, two groups of participants (neutral and reward) worked through the same version of the AX-CPT used in Experiment 1A. In order to keep Experiment 1B comparable to Experiment 1A (and previous research of our laboratory with the AX-CPT), both groups received neutral IAPS pictures before every trial (see the Appendix B for the numbers of the specific IAPS pictures). Neutral IAPS pictures were also shown in the baseline block to align potential differences in valence and arousal levels between the participants. In order to keep the procedure as comparable as possible between the reward and neutral group, a yellow Euro symbol (€, in 48-point bold Arial font) – instead of 5€ pictures as in Experiment 1A – served as reward cue for the reward group in Block 1 and was presented centrally and superimposed on the IAPS picture (cf. Fröber & Dreisbach, 2014, 2016a). The reward cue is supposed to further increase cue maintenance and was therefore shown on every trial. The structure of a target trial was identical to Experiment 1A (see Figure 1).

Both groups started with one practice block of 20 trials without any manipulation. A baseline block of 80 trials (without any manipulation) was presented (80 trials; 56 AX, 8 AY, 8 BX, 8 BY) to determine the individual RT cutoff (see Experiment 1A) for the reward group. Participants of the reward and neutral group received neutral IAPS pictures in this baseline block, and in Block 1(AX-70, with 160 trials each: 112 AX, 16 AY, 16 BX, 16 BY) as well as in Block 2 (AX-40, with 160 trials each: 64 AX, 64 AY, 16 BX, 16 BY). Only in the reward group a reward manipulation was employed in Block 1 indicated by the yellow Euro symbol that was shown on each trial. Then both groups received Block 2 (AX-40) with altered proportions of AX and AY trials. Participants of the reward group again had no a priori knowledge about reward availability until before Block 1, where they were informed that they could win 0.03 € on each trial for fast and correct responses. Before Block 2 participants were informed that reward incentives were no longer available. Participants were never informed about the frequency of the trial types.

Data analysis and Design. For the analysis of performance data practice and baseline trials as well as the first trial of Block 1 and Block 2 were excluded. In addition, error trials were excluded prior to the mean median RT analyses. In order to investigate different time courses for the shift away from increased cue maintenance for the reward and neutral group, we performed a split-block analysis. That is, for the data analysis, Block 1 and Block 2 were split into two halves, each. All split blocks included the respective trial type frequency of AX-70

(Block 1.1 and Block 1.2 of 80 trials each: 56 AX trials, 8 AY trials, 8 BX, 8 BY) or AX-40 (Block 2.1 and Bock 2.2 of 80 trials each: 32 AX, 32 AY, 8 BX, 8 BY).

To examine the effects of reward, we analyzed changes in the behavioral performance *between* participants over the blocks. To this end, a 2 (group: reward, neutral) x 4 (block: 2 x AX-70 vs. 2 x AX-40) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors design was used. Cue-probe condition and block were manipulated within participants, group was a between factor. Error rates (in %) and Reaction times (RTs, in milliseconds) served as dependent variables.

For the sake of simplicity, we focus on error rates especially on AX and AY trials which are the best indicators for increased / decreased cue maintenance. More detailed analyses of error rates and RTs can be found in the Supplementary Materials (a link to the entire raw data set will be made available). There are three important comparisons in order to test our hypothesis of increased cue maintenance and decreased flexibility under reward conditions: The between group comparisons of error rates on AY trials, the between block comparisons of error rates on AY trials as well as the within group comparisons of error rates on AX and AY trials. Differences on AY trials between a reward and a neutral group (= AY errors - between group comparisons) are highly indicative for the increased cue usage under reward conditions (Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a; Locke & Braver, 2008). Higher error rates on AY trials as compared to AX trials *within* the AX-40 blocks (= AX-AY errors - within group comparisons) are a sign for the persistent usage of the A-cue. Comparable performances on AX and AY trials instead – due to a drop in AY errors from the AX-70 to the AX-40 blocks (= AY errors - between block comparisons) – can be interpreted as a successful shift away from cue maintenance (Redick, 2014). Now, for the reward group, we expected higher error rates on AY trials as compared to the neutral group in the AX-70 blocks (Block 1.1 and Block 1.2) (replicating the typical reward effect) and the AX-40 blocks (Block 2.1 and Block 2.2) (confirming our hypothesis of a reward induced decrease in flexibility). The reward induced decrease in flexibility should be further confirmed by a slower alignment of error rates in AX and AY trials due to a gradual drop in AY errors over the course of the AX-40 blocks. For the neutral group, we expected a rapid adaptation to the AX-40 task conditions which should result in similar performance on AX and AY trials already in the first AX-40 block 2.1. The drop in AY errors from the second AX-70 to the first AX-40 block is also reported as a proportional change score in order to take into account group differences in AY errors in the second AX-70 block (Block 1.2).

Results

Error Rates. Mean error rates were entered into a 2 (group: reward, neutral) x 4 (block: 2 x AX-70 vs. 2 x AX-40) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 3). All main effects and interactions reached significance (all *F*s > 9.96, all *p*s < .001). Most importantly, the three-way interaction of Group x Block x Cue-probe condition reached significance, $F(9, 342) = 12.83$, $p < .001$, $\eta_p^2 = .25$. A more detailed report of the results can be found in the Supplementary Materials.

AY errors – Between group comparisons. In accordance with our predictions, planned comparisons yielded higher error rates especially on AY trials in the reward group as compared to the neutral group in both AX-70 blocks (both *F*s > 16.36, both *p*s < .001, 43.4% vs. 12.8%, 52.5% vs. 11.9%) as well as in both AX-40 blocks (both *F*s > 7.1, both *p*s < .01, 15.6% vs. 4.3%, 8.4% vs. 2.8%). These performance differences in AY errors between the groups are higher in Block 1.2 (41%) than in Block 2.1 (12%). This was confirmed by a significant interaction contrast Block x Group in AY trials only, $F(1, 38) = 26.1$, $p < .001$.

AY errors – Between block comparisons. For the neutral group, there was a slight drop in error rates on AY trials from Block 1.2 to Block 2.1 ($p = .07$, 11.9% vs. 4.3%). The drop from Block 2.1 to Block 2.2 was far from significance ($p = .4$, 4.3% vs. 2.8%). The reward group instead showed a significant drop in error rates on AY trials from Block 1.2 to Block 2.1 ($F(1, 38) = 82.87$, $p < .001$, 52.5% vs. 15.6%) and a further significant drop from Block 2.1 to Block 2.2 ($F(1, 38) = 17.8$, $p < .001$, 15.6% vs. 8.4%) suggesting a gradual adjustment over the course of the AX-40 blocks. We calculated the proportional change score for the Block 1.2 to Block 2.1 drop in AY errors by dividing the absolute change in AY errors from Block 1.2 to Block 2.1 by the AY error rate in Block 1.2 for each group separately. The proportional change score of the reward group (70.3%) is comparable to that of the neutral group (63.9%) indicating a comparable relative reduction in cue maintenance.

AX-AY errors – Within group comparisons. To further examine whether the participants still used the A-cue in the AX-40 blocks, we compared AX and AY trial performance in Block 2.1 and Block 2.2 *within* each group. The neutral group showed comparable AY and AX errors in both AX-40 blocks (both *F*s < 1.02, both *p*s > .32) indicating a complete and rapid shift away from stable cue maintenance[13]. By contrast, and despite the significant drop in AY errors from

[13] Please note that in both AX-70 blocks, the neutral group made significant more errors on AY trials than on AX (both *F*s > 5.2, both *p*s < .03) as well as on BY trials (both *F*s > 5.57, both *p*s < .02) indicating increased cue maintenance which is no longer observable on AX-40 blocks.

Block 1.2 to Block 2.1, the reward group showed still significantly higher error rates on AY trials than on AX trials ($F(1, 38) = 14.93$, $p < .001$, 15.6% vs. 7.2%) indicating a still increased cue maintenance. In Block 2.2, there was no longer a performance difference on AY and AX trials ($F(1, 38) = .08$, $p = .78$, 8.4% vs. 7.8%).

Taken together, despite the comparable relative reduction in cue maintenance for both groups, the reward group showed signs of still increased cue maintenance in Block 2.1 but no longer in Block 2.2 due to a further drop in AY errors indicating an adaptation process that was extended over the course of the AX-40 blocks. To sum up, the results suggest a reward induced inertia leading to a delayed adaptation to changed task conditions.

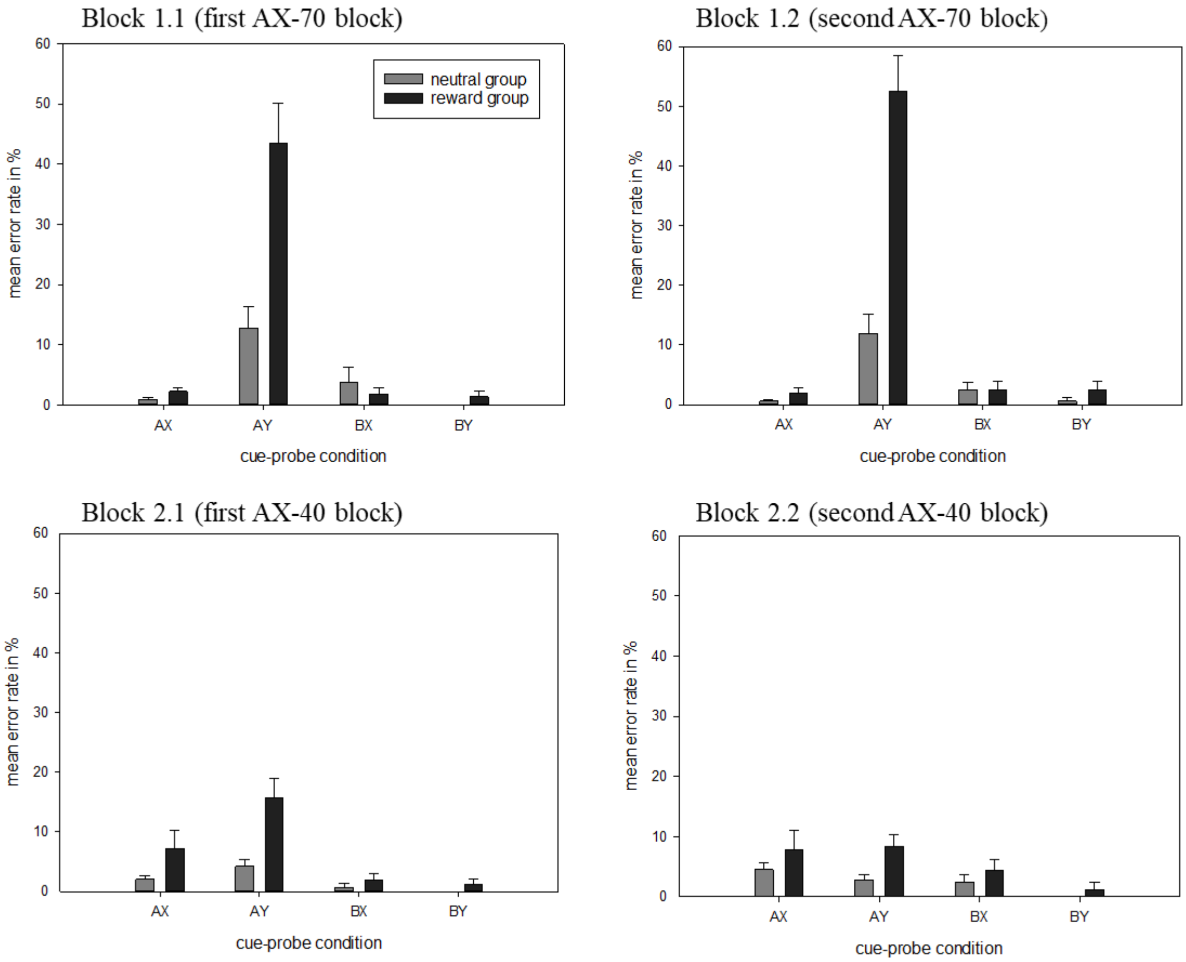


Figure 3. Experiment 1B: Mean error rates of Block 1.1 (upper left panel), Block 1.2 (upper (right panel), Block 2.1 (lower left panel) and Block 2.2 (lower right panel) as a function of cue-probe condition and group (neutral [gray bars] vs. reward [black bars]). Error bars represent one standard error of the mean.

RT data. Mean median RTs were entered into a 2 (group: reward, neutral) x 4 (block: 2 x AX-70 vs. 2 x AX-40) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 4)[14]. All effects and interactions reached significance (all *F*s > 7.57, all *p*s < .001) except for the main effect of block, the interaction of Cue-Probe Condition x Group as well as the three-way interaction (all *F*s < 1.41, all *p*s > .24). Importantly, the analysis revealed a significant interaction Block x Group, $F(3, 108) = 7.57$, $p < .001$, $\eta_p^2 = .17$ (a more detailed report of the results can be found in the Supplementary Material). Planned comparisons showed significantly faster RTs in Block 1.2 than in Block 1.1 in the neutral group ($F(1, 36) = 8.17$, $p < .01$, 372 ms vs. 395 ms). There was no further significant decrease or increase in RTs from Block 1.2 to Block 2.1 and to Block 2.2 (*F*s < 3.9, *p*s > .06). The reward group showed a significant increase in RTs from Block 1.2 to Block 2.1 ($F(1, 36) = 5.5$, $p < .05$, 273 ms vs. 293 ms). The reward group responded significantly faster in all blocks as compared to the neutral group (all *F*s > 7.68, all *p*s < .01).

Taken together, despite their significant increase in RTs from Block 1.2 to Block 2.1, the reward group showed significantly faster RTs through the whole experiment. This can be interpreted as a sign for increased cognitive stability (i.e., increased cue maintenance) across all blocks originally triggered by reward incentives in the first block.

[14] Only 18 participants were included into the RT analyses because two participants had an AY error rate of 100% in Block 1.1 or Block 1.2.

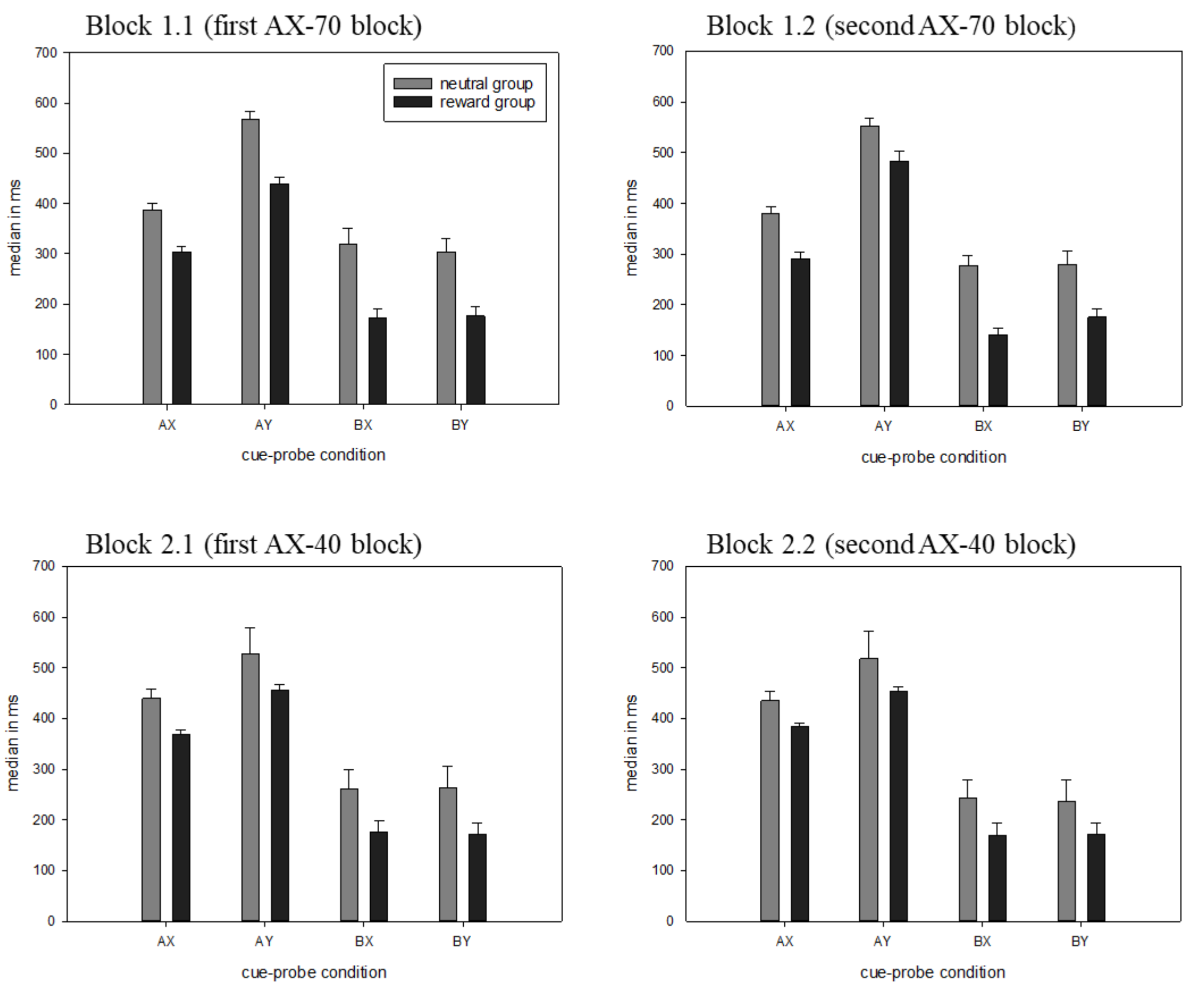


Figure 4. Experiment 1B: Reaction times of Block 1.1 (upper left panel), Block 1.2 (upper right panel), Block 2.1 (lower left panel) and Block 2.2 (lower right panel) as a function of cue-probe condition and group (neutral [gray bars] vs. reward [black bars]). Error bars represent one standard error of the mean.

Discussion

The usually used version of the AX-CPT strongly favors a bias toward increased cue usage due to its efficiency (Hefer & Dreisbach, 2018; Paxton et al., 2006). Therefore, purpose of Experiment 1B was to examine whether the results of Experiment 1A (providing a first hint for the persistent nature of reward induced cue maintenance) were merely evoked by the AX-CPT structure. Crucially, in Block 2.1 and Block 2.2 (AX-40 blocks) the efficiency of cue maintenance was strongly decreased by two modifications: reward availability - associated with an increase in cue maintenance - was taken back in the reward group (as in Experiment 1A) *and* additionally the predictive validity of the A-cue was eliminated. Thus, less cue maintenance (as compared to AX-70 blocks 1.1/2) was more advantageous for successful task execution (see

Redick, 2014). In short, the results are perfectly consistent with Experiment 1A and previous studies (Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a; Locke & Braver, 2008): Once again, the typical reward effect associated with increased cognitive stability in terms of increased cue maintenance was replicated. This time, the effect was shown by comparing a reward group (worse performance on AY trials) with a neutral group. Remarkably, participants of the reward group continued utilizing the context information at least in the first AX-40 block even though it was no longer advantageous. This was evidenced by higher error rates on AY trials as compared to the neutral group (between group comparisons) as well as higher error rates on AY trials as compared to AX trials in Block 2.1 (within the reward group). The results do not mean that the reward group did not adapt at all: There was a significant drop in AY errors from the second AX-70 block to the first AX-40 block (this drop was only marginally significant for the neutral group) leading to a *relative* reduction in cue maintenance (70%) that was comparable to that of the neutral group (64%). Thus, the reward group adjusted cognitive control (reduced utilization of the A-cue information) to the new task conditions but this adaptation process was delayed as evidenced by a further significant drop in AY errors from the first to the second AX-40 block. This drop was again nonsignificant for the neutral group suggesting that the adaptation process toward reduced cue maintenance was still in progress in the reward group. Participants of the neutral group flexibly adjusted their cognitive control mode toward a reduced cue usage leading to performance advantages. This was indicated by comparable AX and AY performance already in the first AX-40 block. The data pattern in RTs in terms of generally faster RTs even in the nonreward AX-40 blocks in the reward group as compared to the neutral group confirmed our assumption of perseverative cue maintenance even in the AX-40 blocks.

In order to confirm and extend our findings of a reward induced increase in cue maintenance at the cost of decreased cognitive flexibility two modifications were made in Experiment 1C. First, we increased the task demands such that the cue no longer allowed for response preparation but only for rule preparation. This modified version was already used in a recent study of our laboratory confirming its sensitivity for shifts in cue maintenance even in the absence of any motivation or affect manipulation (Hefer & Dreisbach, 2016). By modifying the AX-CPT into a two-choice task, we aim to rule out that the former data pattern reflect a mere response priming (for an overview see Henson, Eckstein, Waszak, Frings, & Horner, 2014) which was reinforced by reward incentives in the AX-70 blocks and, as a consequence, still active in the nonreward AX-40 blocks. This observation converges with findings from a study by Muhle-Karbe and Krebs (2010) who showed that reward strengthens the association between actions and their outcomes. Likewise, Waszak and Pholulamdeth (2009) found stronger stimulus-response bindings for episodes that were rewarded with positive pictures. With a more complex AX-CPT, we can further rule out that our results are limited to simple cueing paradigms in which maintaining context information is not challenging our cognitive system. Thus, it might be that higher demands on cue maintenance promote rather than delay an adaptation to changed task conditions in order to save cognitive resources. Second, we included an additional reward group that received reward in both the AX-70 *and* the AX-40 block. Thereby, we can further investigate the hypothesized downside-effect of reward in terms of decreased cognitive flexibility by showing that it is even more pronounced in the context of continuous reward prospect. For Experiment 1C, we predict that reward availability in the AX-70 block should again delay the adjustment to changing task conditions in the AX-40 block. We further predict that ongoing reward availability in the AX-40 blocks should keep cue maintenance on a high level even though this strategy would no longer be adaptive.

Experiment 1C

In Experiment 1C the same procedure as in Experiment 1B was used except that the cue allowed for rule maintenance and preparation only. This time, we compared performance of a neutral group (no reward availability) with *two* other reward groups: In one group reward was available in the AX-70 block only identical to the reward group in Experiment 1B (hereafter Rew-Neut group), in the other group reward was available in the AX-70 *and* AX-40 block (hereafter Rew-Rew group). A data pattern of still increased cue maintenance in the AX-40 block in the Rew-Rew group would be even more evidence for the decreased cognitive flexibility under reward condition because this time overall accuracy and actual reward reception would suffer from this inertia. We expected to replicate the findings of Experiment 1B in terms of a reward induced increase in cue maintenance coming along with decreased flexibility. This downside-effect of reward should be more pronounced in the Rew-Rew group as compared to the Rew-Neut group.

Method

Participants. A total of 94 undergraduate students from the University of Regensburg participated for course credit. 92 participants were included in the final data analysis (75 female, 17 male, mean age = 23.2 years, *SD* = 3.6, range 19 - 37). Two participants of the neutral group were excluded due to extremely high error rates in the baseline block (54.3% and 45.6% vs. 12.2% of the remaining participants in the neutral group). 32 participants were assigned to the neutral group, 30 participants to the Rew-Neut group and 30 participants to the

Rew-Rew group. Participants had no prior knowledge about reward availability. All participants signed informed consent and were debriefed after the session.

Apparatus. The apparatus was identical to Experiment 1B. Responses were collected using a QWERTZ keyboard, with the “down arrow” and “up arrow” keys serving as response keys.

Material and procedure. The material and procedure was the same as in Experiment 1B, except that the cue (A or B) was followed by one or two probes (X or Y). That is, the cue no longer allowed for response preparation but for rule preparation only. Frequent target trials (AX) required a target response rule (e.g. one X-probe – down arrow key, two X-probes – up arrow key), non-target trials (AY, BX, BY) required the reversed response rule (e.g. one probe – up arrow key, two probes – down arrow key). The response mapping was counterbalanced across participants. In Block 1 AX trials were presented with a frequency of 70%, all other trials (AY, BX and BY) with 10% each. In Block 2 (AX-40) AX and AY trials occurred with the same frequency of 40%. BX and BY trials were still presented with a frequency of 10% each. Comparable to the usually used version of the AX-CPT, strong cue usage should result in performance costs in AY trials in the AX-70 block because the cue-triggered target rule has to be overcome.

All groups started with one practice block of 40 trials without picture presentation. A baseline block of 80 trials (without any manipulation) was presented (80 trials; 56 AX, 8 AY, 8 BX, 8 BY) to determine the individual RT cutoff for the reward group (see Experiment 1A and 1B). As in Experiment 1B, participants of all groups received neutral IAPS pictures in the baseline block, in the AX-70 block 1 (160 trials) as well as in the AX-40 block 2 (160 trials). In the Rew-Neut group reward was available in the Block 1 only indicated by the yellow Euro symbol that occurred on every IAPS picture. In the Rew-Rew group reward was available across all blocks and consequently the Euro symbol occurred also on the IAPS pictures in Block 2. Right before Block 1, both reward groups were informed that they could win 0.03 € on each trial for fast and correct responses in the following trials. Before Block 2 participants of the Rew-Neut group were informed that reward was no longer available. Participants of the Rew-Rew group were informed that they could further increase their earnings in the following block. None of the groups were informed about the frequency of the trial types and the change thereof in the last two blocks.

Data preprocessing and Design. For the analysis of performance data practice and baseline trials as well as the first trial of Block 1 and Block 2 were excluded. In addition, error trials were excluded prior to the mean median RT analyses. For the data analysis, Block 1 and Block 2 were again split into two halves, each (see Experiment 1B). All split blocks included the respective trial type frequency of AX-70 (Block 1.1 and Block 1.2 of 80 trials each: 56 AX trials, 8 AY trials, 8 BX, 8 BY) or AX-40 (Block 2.1 and Bock 2.2 of 80 trials each: 32 AX, 32 AY, 8 BX, 8 BY).

To investigate the supposed reward effect associated with increased cue maintenance at the expense of decreased flexibility, we analyzed changes in the behavioral performance between groups over the four blocks. To this end, a 3 (group: neutral, Rew-Neut, Rew-Rew) x 4 (block: 2 x AX-70 vs. 2 x AX-40) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors design was used. Cue-probe condition and block were manipulated within participants, group was a between factor. Error rates (in %) and Reaction times (RTs, in milliseconds) served as dependent variables.

For the sake of simplicity, we focus - as in Experiment 1B - on between group comparisons in AY error rates, between block comparisons in AY error rates and within group comparisons in AX vs. AY error rates. A more detailed analysis of error rates and RTs can be found in the Supplementary Materials. In a recent study from our lab (Hefer & Dreisbach, 2016) we compared trials without potential reward of a reward group with corresponding trials of a neutral group. The data pattern in error rates confirmed a sustained shift towards increased cue maintenance within the reward group as indicated by selectively increased AY errors as compared to the neutral group. Based on this research, we expected to replicate the typical reward effect in terms of increased cue maintenance: Both reward groups should show higher error rates on AY trials in the AX-70 blocks (Block 1.1 and Block 1.2) as compared to the neutral group (AY errors – between group comparisons). In accordance with our hypothesis and the results of Experiment 1B, we expected decreased flexibility in the Rew-Neut and Rew-Rew group. That is, we expected that the error rates on AY trials would only gradually drop from Block 1.2 to Block 2.1 and further to Block 2.2 (AY errors - between block comparisons) but remain on a higher level than AX errors (AX-AY errors - within group comparisons) and also on a higher level than compared to AY errors of the neutral group (AY errors - between group comparisons).

Results

Error Rates. Error rates were entered into a 3 (group: neutral, Rew-Neut, Rew-Rew) x 4 (block: 2 x AX-70 vs. 2 x AX-40) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 5). All effects and interactions reached significance (all *F*s > 2.27, all *p*s < .002), except for the interaction Block x Group ($p = .06$). Most importantly, the three-way interaction reached significance, $F(18, 801) = 2.27$, $p < .01$, $\eta_p^2 = .05$.

***AY errors – Between group comparisons*.** Planned comparisons on the significant three-way interaction revealed the typical reward effect in terms of higher error rates on AY-trials in Block 1.1 and Block 1.2 in the Rew-Neut group as compared to the neutral group (both Fs > 8.95, both ps < .004, 40% vs. 15%, 34% vs. 19%) as well as in the Rew-Rew group as compared to the neutral group (both Fs > 9.97, both ps < .002, 39% vs. 15%, 35% vs. 19%). In Block 2.1 (first AX-40 block), the Rew-Neut group still made significantly more errors on AY trials than did the neutral group ($F(1, 89) = 5.55$, $p < .05$, 19% vs. 11%). This comparison was nonsignificant for Block 2.2 ($p = .61$, 14% vs. 12%). The Rew-Rew group made still more errors on AY trials than did the neutral group in Block 2.1 and in Block 2.2 ($F > 20.2$, $p < .001$, 29% vs. 11%, 27% vs. 12%). The Rew-Rew group made also more errors on AY trials than did the Rew-Neut group in Block 2.1 and Block 2.2 ($F > 9.5$, $p < .01$, 29% vs. 19%, 27% vs. 14%).

***AY errors – Between block comparisons*.** The neutral and Rew-Neut group both showed a significant decrease of AY errors from Block 1.2 to Block 2.1 (both Fs > 7.53, both ps < .01). In the Rew-Neut group there was a further significant drop in AY errors from Block 2.1 to Block 2.2 ($F(1, 89) = 8.08$, $p < .01$, 19% vs. 14%). Within the Rew-Rew group there was no significant drop in AY errors observable neither from Block 1.2 to Block 2.1 nor from Block 2.1 to Block 2.2 (both Fs < 3.25, both ps > .07). The Rew-Neut (44%) and neutral group (41%) showed comparable proportional change scores from Block 1.2 to Block 2.1 indicating a comparable relative reduction in cue maintenance. Whereas the Rew-Rew group showed smaller relative reduction in AY errors of 15% from block 1.2 to Block 2.1.

***AX-AY errors – Within group comparisons*.** Planned comparisons *within* each group should clarify whether the performance on AX trials is similar to that of AY trials in the AX-40 blocks. The analyses revealed significantly higher error rates on AY trials than on AX trials in all three groups across both AX-40 blocks (all Fs > 9.3, all ps < .003)[15]. In order to show whether this AX-AY performance difference differs between the neutral group and Rew-Neut group, an interaction contrast Group (neutral, Rew-Neut) x Cue-Probe Condition (AX, AY) in Block 2.1 errors and Block 2.2 errors was conducted. The AX-AY performance difference was significant for Block 2.1 ($F(1, 89) = 4.3$, $p < .05$, 12% vs. 6%) and nonsignificant for Block 2.2 ($p = .8$, 7% vs. 8%). In order to show whether the AX-AY performance difference differs between the neutral group and Rew-Rew group an interaction contrast Group (neutral, Rew-Rew) x Cue-Probe Condition (AX, AY) in Block 2.1 errors and Block 2.2 errors was conducted. The AX-

[15] Please note that all groups showed higher error rates on AY trials than on AX trials also in the AX-70 blocks (all Fs > 10.61, all ps < .01).

AY performance difference was significantly higher in the Rew-Rew group than in the neutral group for both blocks (both *F*s > 10.8, both *p*s < .001, 22% vs. 6%, 18% vs. 8%) suggesting that the adaptation process to new task conditions was still not accomplished at the end of Block 2.2 (second AX-40 block). The AX-AY performance difference was also significantly higher in the Rew-Rew group than in the Rew-Neut group for both AX-40 blocks (both *F*s > 12.32, both *p*s < .001, 22% vs. 12%, 18% vs. 7%).

Taken together, all groups showed higher error rates on AY trials than on AX trials suggesting an increased usage of the A-cue. This AX-AY difference on error rates – and consequently the usage of the A-cue – was the highest for the Rew-Rew group.

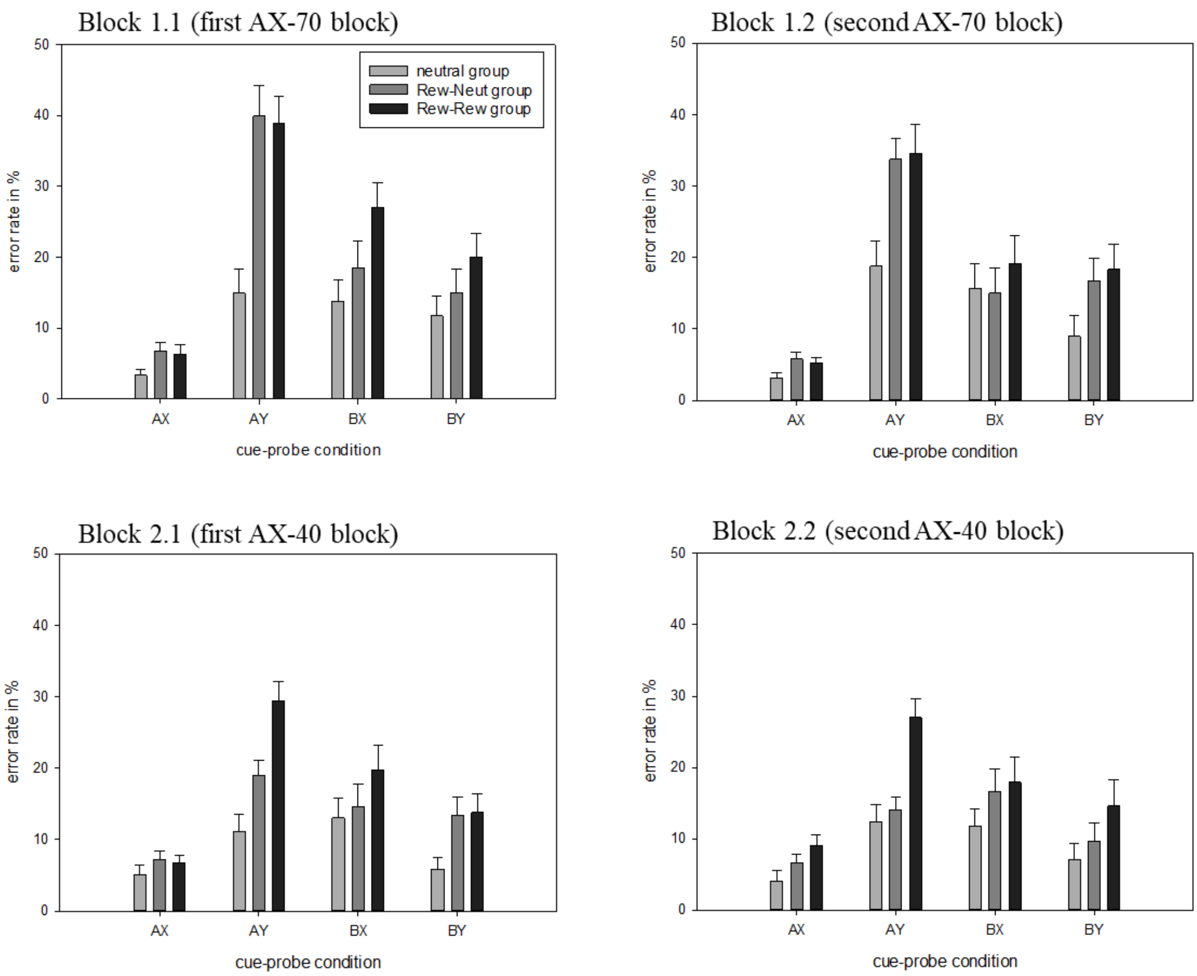


Figure 5. Experiment 1C: Mean error rates of Block 1.1 (upper left panel), Block 1.2 (upper right panel), Block 2.1 (lower left panel) and Block 2.2 (lower right panel) as a function of cue-probe condition and group (neutral [light gray bars] vs. Rew-Neut [dark gray bars] vs. Rew-Rew [black bars]). Error bars represent one standard error of the mean.

RT data. RTs were entered into a 3 (group: neutral, Rew-Neut, Rew-Rew) x 4 (block: 2 x AX-70 vs. 2 x AX-40) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 6). All main effects and interactions reached significance (all *F*s > 2.25, all *p*s < .01). Importantly, the interaction Group x Block x Cue-Probe Condition, $F(18, 801) = 2.25$, $p < .01$, $\eta_p^2 = .05$, reached significance (a more detailed report of the results in RT data can be found in the Supplementary Materials). Planned comparisons on the significant three-way interaction revealed lower RTs on AY trials in both reward groups as compared to the neutral group in Block 1.1, Block 1.2 as well as in Block 2.1 (all *F*s > 6.82, all *p*s < .01) suggesting a delayed adaptation to changed task conditions in the Rew-Neut group. In Block 2.2, there was no longer a performance difference between the Rew-Neut and neutral group (p = .13, 815 ms vs. 885 ms), but still between the Rew-Rew and neutral group ($F(1, 89) = 34.17$, $p < .001$, 619 ms vs. 885 ms). The Rew-Rew group and Rew-Neut group only differed on AY trials in Block 2.1 and Block 2.2 (all *F*s > 10.9, all *p*s < .001) due to a descriptive increase of RTs from Block 1.2 to Block 2.1 in the Rew-Neut group ($p = .2$, 785 ms vs. 819 ms) and a significant decrease in RTs in the Rew-Rew group in AY trials from Block 1.2 to Block 2.1 ($p = .005$, 715 ms vs. 640 ms). Within the neutral group, RTs on AY trials were significantly faster in Block 2.1 than in Block 1.2, $F(1, 89) = 10.69$, $p < .01$, 1041 ms vs. 958 ms, indicating a shift away from cue usage (faster AY RTs are indicative for decreased cue maintenance because under decreased cue usage there should be less target rule activation triggered by the A-Cue).

Taken together, although there is no longer an RT threshold to overcome in the Block 2.1 for the Rew-Neut group, participants showed still significantly lower AY RTs as compared to the neutral group indicating some kind of inertia to adapt to changed task conditions.

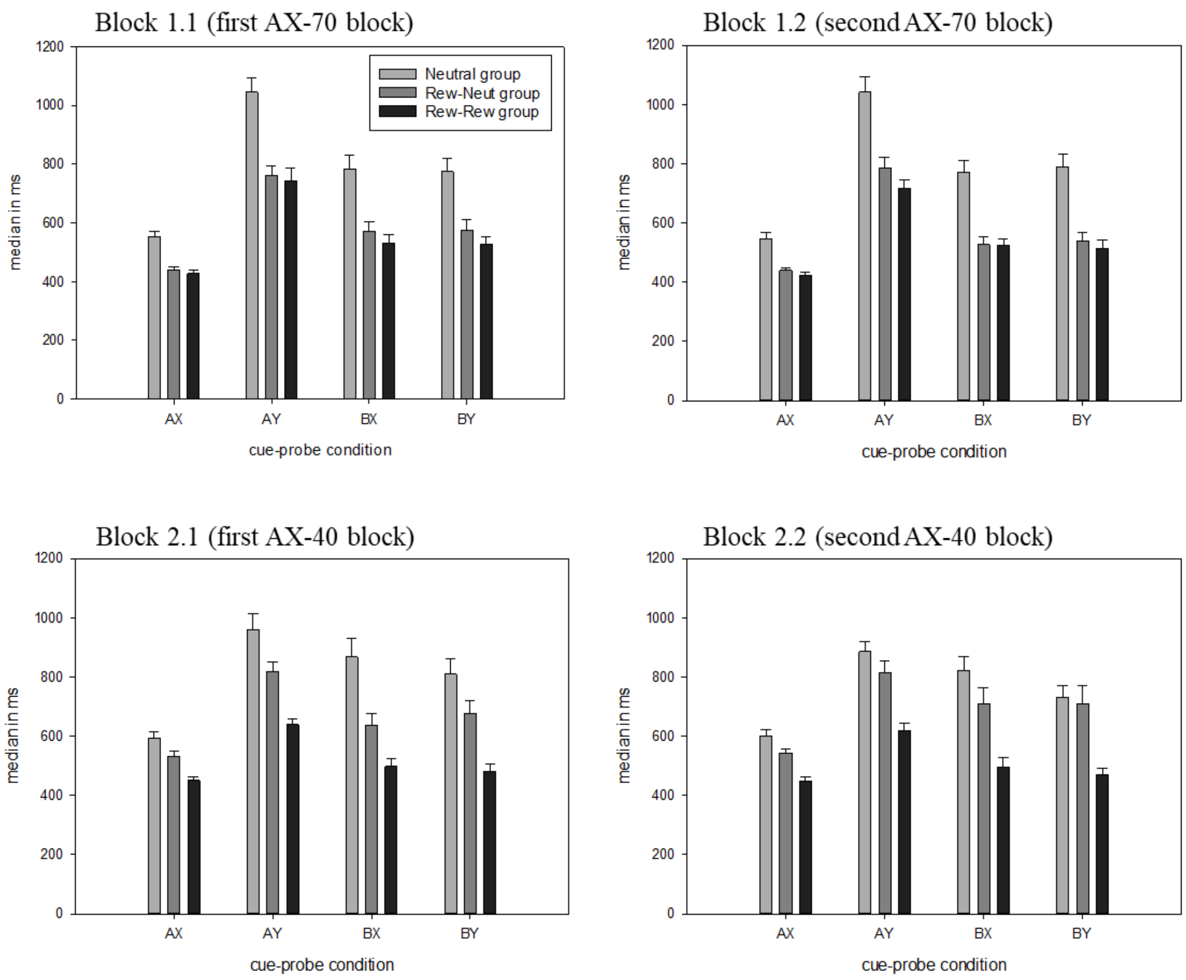


Figure 6. Experiment 1C: Reaction times of Block 1.1 (upper left panel), Block 1.2 (upper right panel), Block 2.1 (lower left panel) and Block 2.2 (lower right panel) as a function of cue-probe condition and group (neutral [light gray bars] vs. Rew-Neut [dark gray bars] vs. Rew-Rew [black bars]). Error bars represent one standard error of the mean.

Discussion

In Experiment 1C we aimed to extend our former findings. By modifying the AX-CPT into a two-choice task, we aimed to investigate whether our results are restricted to simple response priming paradigms with rather low demands on cognitive control. By including a second reward group with reward availability in both, AX-70 and AX-40 blocks, we aimed to investigate whether the downside-effect of reward is more pronounced in the context of *continuous* reward as compared to a context of transient reward.

The results presented in Experiment 1C are consistent with those of Experiment 1B: performance-contingent reward increased cue maintenance as evidenced by higher error rates on AY trials in AX70 blocks in both reward groups as compared to the neutral group. Thus, the motivational effect of reward goes beyond mere response priming (cf. Hefer & Dreisbach, 2016). More interestingly, both reward groups made significantly more errors on AY trials as compared to the neutral group even in Block 2.1 (first AX-40 block) when cue maintenance was no longer efficient. In Block 2.2 (second AX-40 block) the Rew-Rew group still showed higher error rates on AY trials as compared to the neutral group. That is, when reward was available also in the AX-40 blocks, the AY errors remained on a very high level of 29% in Block 2.1 (first AX-40 block) and 27% in Block 2.2 (second AX-40 block) (vs. 11% and 12% in the neutral group), showing that participants in this group still strongly engaged in cue maintenance. A higher AX-AY performance difference (more errors on AY than on AX trials) in both reward groups as compared to the neutral group in Block 2.1 (first AX-40 block) further confirmed our assumption of still increased cue maintenance. That is, both groups kept using the A-cue more strongly than the neutral group to prepare the target rule even though the A-cue was no longer predictive. This AX-AY performance difference was comparable for the Rew-Neut and neutral group in Block 2.2 (second AX-40 Block) but still higher in the Rew-Rew group as compared to the neutral group. This further confirms that especially continuous performance-contingent reward provokes participants to retain a formerly useful strategy even when task conditions change. The neutral and Rew-Neut groups noticed the changed task demands as evidenced by a significant decrease of AY errors from Block 1.2 (second AX-70 block) to Block 2.1 (first AX-40 block). The relative reduction in cue maintenance between theses was comparable for both groups (44% in the Rew-Neut group vs. 41% in the neutral group). But as in Experiment 1B, the Rew-Neut group showed a further significant decrease of AY errors from the first to the second AX-40 block suggesting an inert reduction in cue maintenance that was still in progress in the second AX-40 block (Block 2.2) due to decreased flexibility. In the neutral group instead there was no further significant drop in AY errors (very small rise from 11.1% to 12.4%). Remarkably, the Rew-Rew group showed no significant drop in AY errors neither from Block 1.2 (second AX-70 block) to Block 2.1 (first AX-40 block) nor from Block 2.1 to Block 2.2 (second AX-40 block). This further confirms that the downside-effect of reward in terms of decreased cognitive flexibility is more pronounced in the context of continuous reward. Data pattern of RTs confirm an inert reduction in cue maintenance in the Rew-Neut group: participants showed still lower AY RTs in Block 2.1 (first AX-40 block) as compared to the neutral group (although there was no further need to respond quickly). Only in the second AX-40 block they adapted to the changed task conditions in terms of slowing their reactions times.

Contrary to our expectations, not only the reward groups but also the neutral group showed higher error rates on AY trials than on AX trials in both AX-40 blocks. As this finding was unexpected it has to be interpreted with caution. It may be that reward incentives and situational factors as task difficulty as well delay the weighting of optimal control modes. Given that task difficulty can increase effort (see for example, the difficulty law of motivation by Ach, 1935) just as reward prospect can, this might be taken as a hint that increasing task difficulty might increase cue usage and - as a consequence - reduce cognitive flexibility.

In sum, Experiment 1C extends the finding of Experiment 1B indicating that reward incentives increase cue maintenance at the expense of decreased flexibility. This effect is not restricted to mere response priming paradigms and even more pronounced in the context of continuous reward.

General Discussion

There is growing evidence that performance-contingent reward reinforces the maintenance of context information, thereby leading to more stable behavior (cf. Chiew & Braver, 2013, 1014; Fröber & Dreisbach, 2014, 2016a; Hefer & Dreisbach, 2016). Derived from the general idea that cognitive stability and flexibility are antagonistic in nature (Dreisbach & Goschke, 2004; Dreisbach, 2006; Goschke & Bolte, 2014; Hommel, 2015), the central question addressed in the current study was whether this reward induced increase in cognitive stability (strong context maintenance) comes at the cost of decreased flexibility (flexible adaptation to changed task contingencies).

The data pattern of Experiment 1A closely replicated the typical reward effect in terms of increased cue maintenance and additionally provided first evidence that the influence of reward does not disappear with its removal. In the contrary, reward continued to have an effect on the following non-reward block as indicated by a persistently increased utilization of contextual cue information. These findings were taken as a starting point for two further experiments confirming and extending the assumption that reward induced cue maintenance persists even when this strategy is no longer adaptive (because reward and/or task conditions changed).

In Experiment 1B, we ruled out that the reported results are evoked by the mere structure of the AX-CPT – favoring the usage of the valid A-cue - rather than by the reward manipulation itself. To this end, we reduced the efficiency of cue usage by eliminating reward availability and the predictive validity of the A-cue in Block 2. Thus, maintaining the A-cue in a preparatory manner was no longer advantageous for successful task execution. Instead, a less stable mode of control was required that allowed to be equally prepared for both the target and the non-target response. Results of Experiment 1B replicated those of Experiment 1A: the prospect of reward led to increased cue maintenance. This effect, however, came at the cost of a delayed adjustment to the changing task conditions: participants of the reward group continued using the A-cue for preparing the target response (as evidenced by higher error rates on AY trials in the first AX 40 block as compared to the neutral condition and higher error rates on AY as compared to AX errors within the reward group) even though (1) reward was no longer available and (2) the A-cue was no longer predictive for the upcoming X-probe. Generally speaking, the reward induced stability in the AX-70 blocks led to some kind of inertia which delayed the adaptation process to the new task conditions over the course of the AX-40 blocks.

To confirm and extend these results, Experiment 1C was conducted with two further modifications. First, we modified the AX-CPT such that the cue allowed for rule preparation only. As a further modification, we included an additional reward group that received reward in all blocks. Results of the AX-70 block once again confirmed the typical reward effect in terms of increased cue maintenance as indicated by selectively higher error rates on AY trials. This shows that the reward effect is not restricted to mere response priming and thus confirms findings from a recent study (Hefer & Dreisbach, 2016). More importantly, this effect of reward induced stability came at the cost of decreased cognitive flexibility as indicated by a delayed adaptation process over the course of the AX-40 block (persistent usage of cue information in the first AX-40 block (Block 2.1) in both reward groups). And this effect was significantly stronger when reward was continuously given (still increased cue usage in the second AX-40 block (Block 2.2) in the Rew-Rew group). This is remarkable because participants now received even more frequent error feedback on AY trials (given that the base rate of AY trials was much higher in the AX-40 block than in the AX-70 block). It thus seems that the continuous reward prospect reduced the adaptation to changes of task conditions even in the face of repeated error feedback. It is intuitively plausible that reward availability should increase the sensitivity for errors simply because errors get punished (no reward). And there is in fact empirical evidence for this assumption. Stürmer et al. (2011) found an enlarged error-related negativity (ERN) and post-error slowing in the context of reward which was taken as evidence for the enhanced subjective value of errors. So, if reward does not decrease (but presumably rather increases) the sensitivity to errors than it must be assumed that participants simply were not able to adapt to the changed task conditions because the rewarded participants still made even more errors in the first and second AX-40 block in AY trials than the neutral group (Block 2.1: 29% vs. 11%, Block 2.2: 27% v 12%). And this might be due either to the fact that participants did not *notice* the change in task conditions because they were too focused on reward reception. Or, it may be due to the fact that reward induced cue maintenance necessarily goes along with a reduced cognitive flexibility and thus, a reduced ability to adapt. The significant reduction in AY errors from the second AX-70 block to the first AX-40 block (and further to the second AX-40 block) in the Rew-Neut group rather supports the latter explanation. That is, participants noticed the change in task conditions but obviously were not able to adapt accordingly. On the other side, the nonsignificant reductions in AY errors in the Rew-Rew group rather support the former explanation or a mixture of both: Participants of the Rew-Rew group may have needed more time in order to notice the changed task conditions due to their strong focus on reward reception. But with increasing time on changed task conditions, participants overcame their inertia and switched their focus from reward reception to the current task demands allowing a gradual initiation of an adaptation process in terms of a reduction in cue maintenance. There may be a further explanation: the prospect of reward may reduce the sensitivity for the validity of contextual cue information. That is, as soon as reward incentives are introduced, participants may search for context information – irrespective of their validity – to be prepared for upcoming events. Such a behavior is advantageous in the AX-70 block but highly disadvantageous in the AX-40 block. This idea fits nicely with a recent study of our laboratory. There we could show that performance contingent reward promotes also the usage of *primes* that were only useful but not necessary to accomplish the task whereas a neutral group did not use these primes proactively (Hefer & Dreisbach, 2016). More research is needed to investigate these open questions of e.g. the extent to which the motivational effect of reward depends on the validity of contextual information.

One might wonder whether our results reflect a pure speed-accuracy tradeoff (SAT) rather than motivational effects of reward. Most studies that investigate the effect of reward prospect use fast and correct responses as a performance criterion for reward reception. The concern of a SAT is therefore not new and has been discussed elsewhere (see Chiew & Braver, 2013; Fröber & Dreisbach, 2016a). The SAT phenomenon predicts a general decrement of accuracy for the sake of speed. Our first argument against a pure SAT effect is that in the study presented here participants were able to earn money only for *both* fast and correct responses. That is, decreased RTs at the cost of accuracy would have resulted in a small reward sum. Consequently, participants had to find the right balance between speed and accuracy. What also speaks against the concern of an SAT is that reward incentives resulted in generally faster RTs, whereas error rates increased *selectively* on AY trials as evidenced by the significant interaction of Cue-Probe Condition x Block in Experiment 1A and Condition x Block x Group in

Experiment 1B and 1C in error rates. Regarding Experiment 1A, there was an increase of error rates selectively on AY trials from the baseline to Block 1. Regarding Experiment 1B and 1C, the reward groups made significantly more errors especially so on AY trials as compared to the neutral group (see Figure 3 and 5). And performance differences between the neutral and reward groups were in most of the cases higher on AY trials than on AX/BX/BY trials – which can be seen from the respective interaction contrasts - indicating a shift towards increased cue maintenance rather than a SAT[16] (a detailed report can be found in the Supplementary Material). In other words, the stronger the A-cue is maintained (stability), the higher the costs particularly on AY trials. We can further rule out that the participants applied a pure speed strategy in terms of always preparing for the target response/rule after the A-cue was presented. With such a strategy participants should have had an error rate of almost 0% on AX trials and 100% on AY trials (cf. Fröber & Dreisbach, 2014). There are a few participants with an error rate of 100% on AY trials in some blocks but none of them had an error rate of 100% across all blocks. Thus, reward incentives increased cue maintenance resulting in generally accelerated RTs but increased error rates especially on AY trials – a data pattern that reflects a motivational effect of reward rather than a pure SAT.

Based on the reported findings of increased stability and decreased flexibility in the context of reward, the question arises whether there is any way to counteract this effect. In other words, is there a possibility to increase cognitive flexibility by way of reward cues?[17] In other words, do reward cues always increase cognitive stability or may they also increase cognitive flexibility when a task requires a flexible shift between task sets? In fact, there is some evidence in the literature on task switching (see Kiesel et al., 2010; Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010) showing that the immediate reward history impacts the direction of the reward effect on the flexibility-stability balance (Shen & Chun, 2011; Fröber

[16] The Rew-Rew group made significantly more errors on BX trials in Block 1.1 and on BY trials in Block 1.2 than did the neutral group. The interaction contrasts Group (Rew-Rew vs. neutral) x Cue-Probe Condition (AY, BX/BY) for error rates in Block 1.1 / Block 1.2 are the only ones that failed to reach significance. We argue that this finding (comparable error rate difference between groups on AY and BX trials in Block 1.1 and on AY and BY trials in Block 1.2) rather supports our assumption of a motivational effect of reward: increased error rates on BX / BY trials are a direct consequence of increased A-cue maintenance because there was a X / Y-probe triggered retrieve of the target rule on BX/BY trials due to a strong association between the X/Y-probe and the (on AX trials often correctly and on AY trials often erroneously applied) target rule (cf. Hefer & Dreisbach, 2016).

[17] For a recent review discussing the difference between reward prospect (which has motivational effects on cognition) and reward reception (which might rather have reinforcing effects and promote associative learning) please see Notebaert and Braem (2015).

& Dreisbach, 2016b; Fröber, Raith, & Dreisbach, submitted). Note that here and in other studies cited above, the reward prospect never changed in magnitude. And such unchanged reward prospect obviously promotes cognitive stability. However, recent evidence suggests that *increasing* reward prospect from one trial to the next in fact promotes flexibility in terms of reduced switch costs (Kleinsorge & Rinkenauer, 2012) and faster RTs selectively in switch trials (Shen & Chun, 2011) whereas unchanged high reward prospect again turned out to promote a more stable behavior as evidenced by increased switch costs (Kleinsorge & Rinkenauer, 2012) and fast RTs on repeat trials (Shen & Chun, 2011). Moreover, Fröber and Dreisbach (2016b) provided first evidence that sequential increases in reward magnitude also promote deliberate task switching as evidenced by an increased voluntary switching rate as compared to unchanged high reward. There is thus growing evidence that trial-to-trial increases in reward expectancy may be one way to counteract the effect of a reward induced decrease in cognitive flexibility. More research is clearly needed to further investigate the immediate reward history on the stability-flexibility balance.

To summarize, our results have shown that the reward effect in terms of increased cue maintenance (Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a; Hefer & Dreisbach, 2016; Locke & Braver, 2008) comes at the cost of decreased cognitive flexibility to adapt to changed reward and task conditions. This is in line with recent reward studies providing evidence for increased stability (Padmala & Pessoa, 2011; Veling & Aarts, 2010) and, as a consequence, decreased flexibility. Consequently, in applied settings the use of reward should be handled with caution considering this potentially negative outcome of reward contingencies. Our study therefore extends research regarding the negative effects of reward (Bonner, Hastie, Sprinkle, and Young, 2000).

Conclusion

Taken together the research presented here brought up two main findings regarding the motivational modulation of the balance between cognitive stability and flexibility: (1) performance-contingent reward prospect increases cognitive stability in terms of increased cue maintenance which comes at the cost of decreased flexibility in terms of a delayed adjustment to changing task conditions. (2) This effect is even more pronounced in the context of sustained reward availability.

Appendix A

Image of 5-Euro Banknote preceding each trial in Experiment 1A

Appendix B

Numbers of affective picture stimuli (Lang et al., 1999)

Neutral: 7000, 7002, 7004, 7006, 7009, 7010, 7020, 7025, 7030, 7034.

Positive: 1440, 1463, 1710, 2050, 2057, 2058, 2250, 2311, 2341, 2345.

Compliance with Ethical Standards

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

Conflict of Interest: Carmen Hefer declares no conflict of interest. Gesine Dreisbach declares no conflict of interest.

The research presented here was supported by a grant from Deutsche Forschungsgemeinschaft DFG: DR 392/7-1 to Gesine Dreisbach.

STUDY 2

Prospect of performance-contingent reward distorts the action-relevance of predictive context information

Carmen Hefer & Gesine Dreisbach

Hefer, C., & Dreisbach, G. (2020). Prospect of performance-contingent reward distorts the action relevance of predictive context information. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *46*(2), 380–399.

Abstract

There is a lot of evidence showing that the prospect of performance-contingent reward increases cue usage and cognitive stability. In a recent study, we showed that rewarded participants even continued using cues when they were no longer predictive of the required response rule, even at the expense of higher errors. In the present study, we aimed to investigate the mechanism underlying this maladaptive perseveration. One possible mechanism was that participants under reward conditions use cue-related stimulus frequencies even when they are not indicative of response rule frequencies. In a series of three experiments, using modified versions of the classical AX-continuous performance task, this hypothesis was confirmed. Taken together, the findings have important implications as they show that the prospect of reward encourages the selective usage of any information that might be relevant for preparatory behavior.

Keywords: Performance-contingent Reward, AX-Continuous-Performance Task, Cue Maintenance, Proactive Control, Stability-Flexibility-Balance, Cue Validity

Supplemental materials: http://dx.doi.org/10.1037/xlm0000727.supp

Introduction

The interplay between the antagonistic control modes of stability and flexibility enables the cognitive system to coordinate and adjust thoughts and actions in accordance to changing context and task demands (e.g., Dreisbach & Fröber, 2019; Goschke, 2003, 2013; Hommel, 2015). One aspect of a stable cognitive control mode allows the maintenance of goals or context-relevant information over time in the face of distraction (referred to as cue maintenance from now on). A flexible cognitive control mode on the other hand allows the switch of goals and behavioral dispositions in response to significant changes in the environment. There has been a long-lasting interest in investigating how the balance between cognitive stability and flexibility is modulated because both control modes are associated with advantages (e.g., strong goal-shielding or flexible set shifting) and disadvantages (e.g., perseverative behavior or increased distractibility). For instance, there is growing evidence suggesting that motivation and emotion play an important role in the stability-flexibility balance (for recent reviews see Dreisbach & Fröber, 2019; Goschke & Bolte, 2014; Hommel, 2015). Reward-induced increases in motivation seem to promote goal maintenance and cognitive stability (Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a; Hefer & Dreisbach, 2016, 2017; Locke & Braver, 2008; for recent reviews on the interaction between motivation and cognition see Botvinick & Braver, 2015; Yee & Braver, 2018). Positive affect instead promotes cognitive flexibility (e.g., Dreisbach, 2006; Fröber & Dreisbach, 2012; Hefer & Dreisbach, 2018; Rowe, Hirsh, & Anderson, 2007; Wang, Chen, & Yue, 2017; Yang & Yang, 2014; Zwosta, Goschke, Hommel, & Fischer, 2013) at the cost of increased distractibility (e.g., Dreisbach & Goschke, 2004). Findings about the positive affect effect are not entirely consistent. For example, Chiew and Braver (2014) found evidence that positive affect can even promote cognitive stability in the standard AX-CPT (but see Hefer and Dreisbach, 2018, who showed the sensitivity of the positive affect effect to strategic influences developed with increasing experience with the given task). Critically for the present study, the prospect of performance-contingent reward enhances cue maintenance even when contextual information was no longer predictive of the required action (Hefer & Dreisbach, 2017). This was taken as evidence that performance-contingent reward increases cognitive stability at the costs of decreased flexibility (cf. Müller at al., 2007). To define cognitive stability in terms of cue maintenance more precisely, we here employ the *Dual Mechanism of Control* (DMC) framework by Braver (Braver, 2012). In his framework, Braver differentiates between two complementary modes of cognitive control: proactive and reactive control (Braver, 2012; Braver, Gray, & Burgess, 2007). A proactive control strategy is defined by a strong maintenance of context or goal-relevant information leading to preparatory activity. A reactive control strategy on the other hand is defined as a just-in-time control that has to be activated by an appropriate bottom-up stimulus trigger (Braver, 2012). Both control strategies have their advantages and disadvantages (Braver et al., 2007): A continuous maintenance of task goals in an activated state (proactive control) allows anticipatory behavior which improves task performance and facilitates task completion. However, such an anticipatory behavior requires the presence of highly reliable contextual cues, which to maintain is thought to be metabolically costly. Therefore, proactive control should be preferentially engaged in situations with high motivational value or with the possibility of reward maximization. On the other hand, the rigid encoding and maintenance of goal-relevant features also has its drawbacks: Due to reduced background monitoring under proactive control, the system runs the risk of missing important information like changes in reward/punishment contingencies (Braver et al., 2007; Hefer & Dreisbach, 2017). Reactive control, by contrast, is a more bottom-up driven control strategy that is relied upon when either advance preparation is not possible, attentional resources are limited or the motivation to put effort into executing a task is rather low. However, there are also notable disadvantages, since this strategy results in slower and less reliable performance than proactive control, as it requires the reactivation of task goals – a time-consuming process - which depends on sufficiently salient trigger events (Braver, 2012).

In the following we refer to cue maintenance as the proactive maintenance and usage of contextual information.

Here we aim to explore in more depth the processes underlying the maladaptive usage of context information under reward conditions found in Hefer and Dreisbach (2017). That is, in a follow-up study to Hefer and Dreisbach (2017), we aim to answer, why rewarded participants perseverated in using no longer action-predictive contextual information even in the face of increased error feedback. A closer look at the cuing paradigm we used in Hefer and Dreisbach (2017) might give an answer to this question.

The (Modified) AX-Continuous Performance Task

The modified version of the AX-continuous performance task (AX-CPT) is highly comparable to the classical version (Servan-Schreiber, Cohen, & Steingard, 1996): Several letters are presented sequentially. The first letter represents the "cue" (A or B), the last letter the "probe(s)" (X/XX or Y/YY). In contrast to the standard version of the AX-CPT, in the modified version the cue A or B is followed by one or two probes. Participants have to respond to the probe(s). In total, there are four different trial-types: AX/AXX target trials, and AY/AYY, BX/BXX, and

BY/BYY non-target trials. Target trials (AX) require the target response rule (e.g., one X – down arrow key, two XX – up arrow key), non-target trials (AY, BX, BY) required the reversed non-target response rule (e.g., one probe – up arrow key, two probes – down arrow key. Thus, the cue only allows rule preparation but no longer response preparation as is the case in the standard AX-CPT (see Hefer & Dreisbach, 2016; 2017). In the following, AX target trials correspond to trials where the cue A is followed by either one X or two XX, the same holds for AY, BX, and BY non-target trials. Importantly, B and Y represent any letter from the alphabet beside A and X whereas A is always A and X is always X. AX target trials require a target response rule (e.g., one X down-arrow key, two XX up-arrow key). In all remaining cue-probe conditions (AY, BX and BY non-target trials) the response rule is reversed (e.g., one probe (any one letter) up-arrow key, two probes (any two letters) down-arrow key). Moreover, in the so-called AX70-AY10 version AX sequences occur with 70% frequency, the non-target trials with 10% frequency each (cf. Hefer & Dreisbach, 2017). Due to this frequency distribution, the A-cue produces a strong expectancy for the X-probe(s). Consequently, the stronger the A-cue is maintained (cognitive stability) the higher the costs if this expectation is hurt and the A-cue is not followed by the expected X/XX probe(s) but by the unexpected Y/YY probe(s). These costs typically show in higher error rates and slower RTs on AY trials as compared to BX trials. Conversely, weak cue maintenance leads to better performance on AY trials (because no cue-triggered target rule bias has to be overcome) and worse performance on BX trials. More precisely, the ratio of errors on AY-BX trials provides information about the degree of proactive / reactive control: increased proactive control elicits more AY errors and comparatively less BX errors. Increased reactive control shows in lower AY errors as compared to BX errors. The advantage of the modified AX-CPT is that it goes beyond a mere response preparation (see also Hefer & Dreisbach, 2016 for further discussion). That means that in the standard AX-CPT, participants could always prepare the target response after an A-cue was presented and the non-target response after a B-cue. Applying this simple strategy would result in higher error rates on AY-trials as compared to all other trial types. As shown in many studies using the standard version of the AX-CPT, performance-contingent reward reinforces this strategy as indicated by highly increased error rates on AY trials relative to a neutral (no-rewarded) control group or block (Fröber & Dreisbach, 2014, 2016a; Chiew & Braver, 2013, 2014; Locke & Braver, 2008). In two preceding studies the reward effect was also found in the modified version of the AX-CPT (Hefer & Dreisbach, 2016, 2017) allowing the conclusion that the reward effect goes beyond mere response preparation but also applies to rule preparation. We therefore applied the modified AX-CPT as it allows for a generalization of the proactive reward effect also to task preparation and eventually to task switching. Moreover, in a recent study from our laboratory, we found that this increased cue maintenance under reward conditions comes at the cost of reduced flexibility to adjust to a changed A-cue validity (Hefer & Dreisbach, 2017). In that study, we compared three groups of participants, one group was continuously rewarded in all blocks (reward group), one group was never rewarded (neutral group) and a third group was rewarded in the first block but no longer in the last block (Rew-Neut group). Moreover, the A-cue validity changed: In the first block (AX70-AY10), the A cue was (as usually) highly predictive of the probe (70% by the X/XX probe/s, and with 10% by the Y/YY probes). In the second block (AX40-AY40, see also Redick, 2014), this A-cue validity was eliminated: The A-cue now was followed by X/XX or Y/YY equally often; consequently, the A-cue was no longer predictive of the required response rule. Results showed that the reward effect (in terms of highly increased AY error rates) not only survived the withdrawal of reward (in the Rew-Neut group) but also delayed the adaptation to changed cue validity conditions. In other words, participants under reward conditions kept using the A-cue to prepare for the X-rule (as evidenced by an unchanged high error rate on AY trials in AX40-AY40 blocks) even though the A-cue was equally predictive of the X-rule and Y-rule.

Here, we aim to look into a possible mechanisms that might underlie this observed reduced flexibility to adapt to the changed A-cue validity: The reward-induced increase in cue maintenance might have led to a confusion of stimulus (probe) frequencies and rule frequencies: in the AX40-AY40 block, the A-cue is no longer predictive of the required response rule (X or Y-response rule) but it is still predictive of the upcoming stimulus (namely the X-probe/s): remember that the Y-probe is a variable and stands for any letter of the alphabet except for the letter A and X whereas the X-probe actually is always the letter X. This means that the A-cue is still predictive of the upcoming stimulus because it is more frequently followed by the X-probe than by any other of the variable Y-probes. Given that reward prospect promotes cue maintenance - which itself depends on valid pre-information - reward-induced cue maintenance might have made participants more vulnerable to use stimulus frequencies for rule preparation even when stimulus frequencies were no longer predictive of rule frequencies. In other words: under reward conditions, unequal stimulus frequencies create stronger expectancies for these stimuli which then promote the proactive activation of the rule (the X-rule) that is associated with the expected stimulus. This phenomenon is also known from other domains, like the overestimation of object frequency that is expected to occur in certain contexts (e.g., the mug in the office; Greene, 2016; cf. Tversky & Kahnemann, 1974). Because in AX40-AY40 blocks, the A-cue is only predictive of the X/XX probes but not of the X-rule (because the Y-rule is equally likely to follow the A-Cue), reward-induced increased usage of stimulus frequencies would result in increased error rates on AY trials. Experiments 2A, 2B, and 2C are designed to directly investigate this assumption.

Experiment 2A

The purpose of Experiment 2A was to investigate the mechanism underlying a rigid cue usage in the context of reward. As already reviewed in the introduction, we propose that under performance-contingent reward, participants may use the higher frequency of the X-probe to prepare for the X-rule even though the Y-rule is equally probable. So far, however, we observed such a rigid cue usage (in AX40-AY40 blocks) only when contextual cues had previously been predictive not only of the upcoming stimulus but also of the required response rule (in AX70-AY10 blocks, Hefer & Dreisbach, 2017). That is, when cue usage had previously been experienced as adaptive. To gain a deeper insight into the mechanism underlying a rigid cue usage, it is important to examine whether this phenomenon also shows up even when cues have never been predictive of the upcoming rule (but only of the upcoming stimulus). To examine this question, three groups of participants were tested. They first worked through an AX40-AY40 block which was then followed by an AX70-AY10 block. One group could receive reward in both blocks (reward group), another group only received reward in the second (AX70-AY10) block (neutral-reward group). The third group (neutral group) never had the chance to gain reward. If the reward group uses A-cue information for action preparation already in the AX40-AY40 block (even though they had never experienced the A-cue usage as adaptive), we should observe higher error rates on AY trials than on AX trials. The neutral-reward and neutral group are not expected to use A-cue information in the AX40-AY40 block and should therefore show comparable error rates on AX and AY trials.

The AX70-AY10 block was employed to examine whether participants would be able to flexibly adjust to new task condition (change from non-predictive to predictive cues) which would be indicated by an increase in the performance difference on AY-BX errors (higher error rates on AY than on BX trials) from the AX40-AY40 to the AX70-AY10 block. An additional reduction in AX errors would further speak to an adjustment to the increased A-cue validity. Such an adjustment was expected in all groups because cue maintenance is the most efficient strategy in AX70-AY10 blocks. For instance, participants assigned to the neutral group in the study conducted by Hefer and Dreisbach (2017) also showed a slightly delayed adaptation to new task conditions (change from predictive to non-predictive cues) suggesting increased cue maintenance in the AX70-AY10 block even without reward manipulation (see also Hefer &

Dreisbach, 2018). However, the adaptation should be most pronounced in the neutral-reward group (as compared to the neutral group) reflecting the typical reward effect of increased cue usage.

Method

Participants. A total of 107 undergraduate students from the University of Regensburg participated for course credit. All participants were included in the final data analysis (73 female, 34 male, mean age = 21.54 years, *SD* = 3.35, range 18 - 46). 35 participants were assigned to the reward group, and 36 participants were assigned to the neutral-reward and neutral group, respectively. Participants had no prior knowledge about reward availability. All participants signed informed consent and were debriefed after the session. The research presented here is part of a research project funded by the Deutsche Forschungsgemeinschaft (DFG) that received ethical approval as a whole.

Apparatus. Participants were tested individually in a lab at the University of Regensburg. The experiment was run on a Dell PC computer with a 17-inch monitor. The viewing distance was approximately 50 cm. The experiment was presented using E-Prime 2.0 (Psychology Software Tools, Sharpsburg, PA). Responses were collected using a QWERTZ keyboard, with the "down arrow" and "up arrow" keys serving as response keys. The response mapping of the target and non-target response rules was counterbalanced across participants (see Table 3).

Table 3. Assignment of cues and probes to correct response keys. Frequency distribution of AX target trials and AY, BX, and BY nontarget trials in AX70-AY10 and AX40-AY40 blocks.

Cue / probe	**X**	**XX**	**Y**	**YY**
	down-arrow key	up-arrow key	up-arrow key	down-arrow key
A	AX target trial (70% in AX70-AY10, 40% in AX40-AY40)		AY nontarget trial (10% in AX70-AY10, 40% in AX40-AY40)	
	up-arrow key	down-arrow key	up-arrow key	down-arrow key
B	BX nontarget trial (10% in AX70-AY10, 10% in AX40-AY40)		BY nontarget trial (10% in AX70-AY10, 10% in AX40-AY40)	

Material and procedure. The material and procedure were comparable to those in the study conducted by Hefer and Dreisbach (2017). Each trial of the AX-CPT consisted of a sequence of letters. The letter A served as cue on AX and AY trials. The letter X served as a probe on AX and BX trials. Target trials (AX) required the target response rule (e.g., one X – down arrow key, two XX – up arrow key), nontarget trials (AY, BX, BY) required the reversed nontarget response rule (e.g., one probe – up arrow key, two probes – down arrow key; see Table 3). In between cue and probe, three distractor letters were presented to increase maintenance demands (cf. Dreisbach, 2006; Fröber & Dreisbach, 2014, 2016a, Hefer & Dreisbach, 2017). B-cues, Y-probes and distractor letters were chosen randomly from the alphabet (beside A and X) without replacement. Cue and probe were presented in magenta (Arial font, bold, size 28), distractor letters were presented in black (Arial font, bold, size 24). All letters were presented centered on a gray background.

To keep the procedure as comparable as possible to Hefer and Dreisbach (2017) and to align potential differences in valence and arousal levels between the participants, all groups received neutral pictures of the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1999) before every trial. The numbers of the specific IAPS pictures are 7000, 7004, 7006, 7009, 7035, 7040, 7080, 7090, 7175, 7233. The mean ratings for the neutral picture set were valence = 4.99 (on a scale from 1 to 9) and arousal = 2.45 (on a scale from 1 to 9). IAPS pictures were presented centered on a gray background in a landscape format, adjusted to a size of 800 x 600 pixel. Picture repetitions were not allowed on consecutive trials. A yellow Euro symbol (€, in 48-point bold Arial font) served as reward cue in the rewarded blocks where it was presented in all trials centrally and superimposed on the IAPS picture (cf. Fröber & Dreisbach, 2014, 2016a; Hefer & Dreisbach, 2017). The trial structure is shown in Figure 7. Each trial began with the presentation of a neutral IAPS picture for 400 ms which was followed by a blank screen for 100 ms. The cue appeared for 300 ms, followed by a blank screen (200 ms) and three distractor letters (each for 300 ms). After another blank screen (200 ms), the probe was presented and remained on the screen until a response was given. Responses were followed by a visual feedback message for 1.500 ms. In the baseline block and no-reward blocks, the German word *Richtig!* (“correct”) in blue was presented after correct responses, the German word *Falsch!* (“wrong”) appeared in red as feedback message after an error was made. In reward blocks, feedback messages were changed to the German sentence *Richtig! Bonus erhalten* (Correct! Bonus won) in green for correct responses below the RT cutoff, *Zu langsam.*

Kein Bonus (Too slow. No bonus)[18] in blue for correct but too slow responses, and *Falsch! Kein Bonus* (Wrong. No bonus) in red for errors. Before the next trial an inter trial interval (blank screen) of 500 ms was presented.

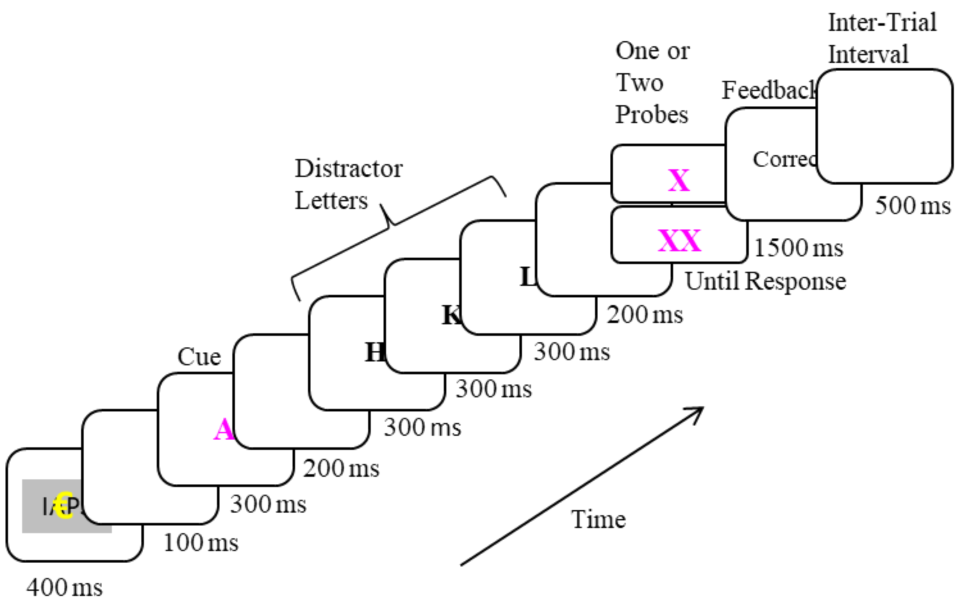


Figure 7. Trial structure of an example AX target trial. A yellow Euro symbol served as reward cue in the reward groups.

All groups started with one practice block of 40 trials (AX40-AY40) without any manipulation that means no IAPS pictures were presented. Participants worked through 40 practice trials to get familiar with the AX-CPT. The presentation of neutral IAPS pictures started with the baseline block (AX40-AY40, 80 trials: 32 AX, 32 AY, 8 BX, 8 BY) which was used to calculate an individual RT threshold. After the baseline block, participants worked through one AX40-AY40 block of 160 trials (AX40-AY40, 160 trials: 64 AX, 64 AY, 16 BX, 16 BY). Then all groups received block 2 (AX70-AY10, 160 trials: 128 AX, 16 AY, 16 BX, 16 BY) with altered proportions of AX and AY trials (see Figure 8). Note that BX and BY nontarget trials always occurred with a frequency of 10% each irrespective of the given block (AX40-AY40 or AX70-AY10).

[18] i.e., within a RT threshold that was calculated for each cue-probe condition (AX, AY, BX and BY) and each individual participant as the fastest 30th percentile of correct baseline block reaction time (see also Fröber & Dreisbach, 2014, 2016a; Hefer & Dreisbach, 2016, 2017).

Participants of the reward group (who had the chance to earn 0.03 € on each trial in both blocks) and neutral-reward group (who had the chance to earn 0.03 € on each trial only in the AX70-AY10 block) had no a priori knowledge about reward availability until the first rewarded block came up. There, they were informed that they could win 0.03 € on each trial for fast and correct responses. A separate feedback message informed them about their reward sum after each reward block. *Participants were never informed about the frequency of the trial types*. They were only informed about the task rule:

> "[…] Please press the down-arrow key button whenever one X appears and the up-arrow key button whenever two XX appear but only if an A was shortly presented before. In all other cases (not an A but another letter is presented prior to the X/XX or the A is followed by another letter than X/XX the response rule is reversed […]"

Moreover, we instructed the participants to ignore the black distractor letters because only the colored cue and probe letters were important to accomplish the task. In addition, we informed them that the cue would be presented only for a short time and that they had to react to the probe only.

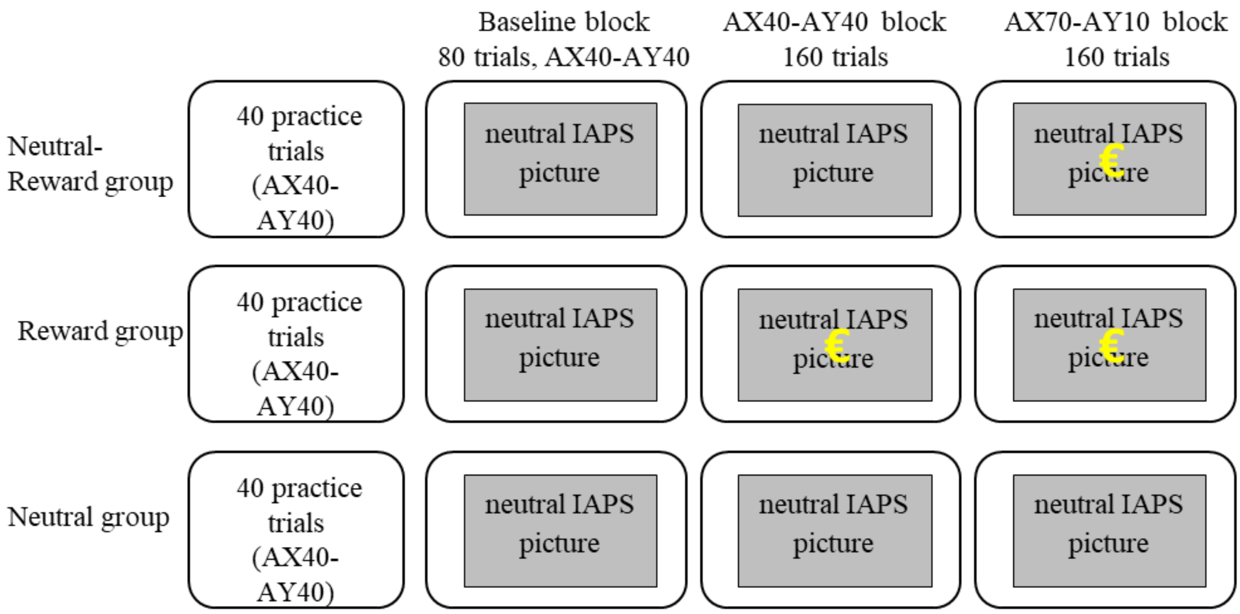


Figure 8. Overview of the block structure of Experiment 2A. The yellow Euro symbol represents reward availability.

Data preprocessing and Design. For the analysis of performance data practice and baseline trials as well as the first trial of each experimental block were excluded. In addition, error trials were excluded prior to the mean median RT analyses. To gain a better understanding of the time course of cue usage and adaptation, for the data analysis, Block 1 and Block 2 were split into two halves each (see also Hefer & Dreisbach, 2017). All split blocks included the respective trial type frequencies of AX40-AY40 (Block 1.1 and Bock 1.2 of 80 trials each: 32 AX, 32 AY, 8 BX, 8 BY) or AX70-AY10 (Block 2.1 and Block 2.2 of 80 trials each: 56 AX trials, 8 AY trials, 8 BX, 8 BY). In the following Block 1.1 and Block 1.2 will be summarized as Block 1.1/2, Block 2.1 and Block 2.2 will be summarized as Block 2.1/2. Please note that there was no break between Block 1.1 and Block 1.2 as well as between Block 2.1 and Block 2.2 to avoid re-start costs.

To test whether the reward group uses the higher frequency of the X-probe to prepare for the X-rule, we analyzed the AX40-AY40 blocks. To this end, a 3 (group: reward, neutral-reward, neutral) x 2 (block: Block 1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors design was used.

To test whether participants (and especially those assigned to the neutral-reward group) would adjust to new task conditions, we analyzed the transition from the second AX40-AY40 block to the AX70-AY10 blocks. To this end, a 3 (group: reward, neutral-reward, neutral) x 3 (block: Block 1.2, Block 2.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors design was used.

Cue-probe condition and block were manipulated within participants, group was a between factor. Error rates (in %) and Reaction times (RTs, in milliseconds) served as dependent variables.

For the sake of simplicity, we will concentrate on AX and AY errors, the ratio of AY and BX errors, and hypothesis-relevant interactions which will be listed in the following. The interaction Group x Cue-probe condition is hypothesis-relevant because it provides information about different levels of cue maintenance between groups in the AX40-AY40 blocks. An interaction with the factor block provides information about the dynamic of cue maintenance which may decrease as soon as participants notice that the A-cue is not informative about the required action. Regarding the transition from the second AX40-AY40 block to the AX70-AY10 blocks, we will focus on the three-way interaction Group x Block x Cue-probe condition and the two-way interaction Block x Cue-probe condition. The interaction Block x Cue-probe condition is relevant because it provides information about an adjustment from the second AX40-AY40 block to the AX70-AY10 blocks across all groups. The three-way interaction is relevant because it provides information about a potential increase in cue maintenance from the second AX40-AY40 block to the AX70-AY10 blocks within a specific group. To keep the result section on error rates as simple as possible main effects and not hypothesis-relevant interactions can be found in the Supplemental Materials. We do not have specific hypotheses regarding analyses on RTs (which – from our experience – are less indicative of the involvement of cue maintenance, see also Fröber and Dreisbach, 2014).

Only the reward group which received reward across all blocks was expected to shift toward increased cue maintenance already in the AX40-AY40 blocks which should result in higher error rates on AY than on AX trials. Especially the neutral-reward group was expected to adjust to new task conditions in terms of a significant increase in cue maintenance (increase in AY errors and decrease in AX errors) from Block 1.2 (second AX40-AY40) to Block 2.1/2 (AX70-AY10 blocks).

Results

Error Rates – Block 1.1/2 (AX40-AY40). Error rates were entered into a 3 (group: reward, neutral-reward, neutral) x 2 (block: Block 1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 9)[19]. Most important for our hypothesis, the interaction between group and cue-probe condition was significant, $F(6, 312) = 3.36$, $p = .003$, $\eta_p^2 = .06$ (see Figure 9).

Within-group comparisons revealed higher error rates on AY trials than on AX trials only within the reward group, $t(34) = 5.51$, $p < .001$, $d = 1.11$. Performance on AY and AX trials also differed significantly within the neutral group, $t(35) = 2.16$, $p = .04$, $d = 0.37$, but not within the neutral-reward group, $t(35) = 1.58$, $p = .12$, $d = 0.24$. Within-group comparison revealed higher error rates on AY trials relative to BX trials, and relative to BY trials only within the reward group, both *t*s > 2.56, both *p*s < .02, both *d*s > 0.47. Error rates on AY trials and BX trials, as well as on AY trials and BY trials did not differ significantly within the neutral-reward group, both *t*s < 1.97, both *p*s > .06, both *d*s < 0.22, and within the neutral group, *t*s < 1.55, both *p*s > .13, both *d*s < 0.29.

Between-group comparisons revealed higher errors rates on AY trials in the reward group compared with both the neutral-reward group, $t(57.992) = 6.55$, $p < .001$, $d = 1.56$, and the neutral group, $t(62.035) = 5.39$, $p < .001$, $d = 1.28$. The reward group committed also more errors on AX trials compared with both the neutral-reward group $t(69) = 2.74$, $p = .01$, $d = 0.65$,

[19] Full tables of means and SDs of all experiments can be found in the Appendix at the end of this article.

and the neutral group, $t(69) = 2.12$, $p = .04$, $d = 0.5$. The performance difference between the reward group and neutral-reward group as well as between the reward group and neutral group was higher on AY trials than on AX trials as indicated by significant interaction contrasts (Group (reward, neutral-reward) x AX/AY, $F(1, 104) = 19.88$, $p < .001$, Group (reward, neutral) x AX/AY, $F(1, 104) = 15.22$, $p < .001$). The neutral-reward group and neutral group did not differ significantly on AY trial performance, $t(70) = 1.18$, $p = .24$, $d = 0.28$, and AX trial performance, $t(70) = 0.58$, $p = .56$, $d = 0.14$. Between-group comparisons showed also higher error rates on B-cue trials in the reward group compared with both the neutral-reward group and neutral group, all *t*s > 2.17, all *p*s < .03, all *d*s > 0.52. More importantly, participants in the reward group made more errors on AY compared with BX trials whereas both neutral groups showed the reverse pattern of descriptively higher error rates on BX trials compared with AY trials. The respective interaction contrast were both highly significant (Group (reward, neutral-reward) x AY/BX, $F(1, 104) = 10.37$, $p = .002$, Group (reward, neutral) x AY/BX, $F(1, 104) = 6.46$, $p = .01$).

Thus, the reward group used the higher frequency of the X-probe to prepare for the X-rule (even though X-rule and Y-rule occurred equally often) resulting in increased errors especially on AY trials.

The interactions Group x Block and Cue-probe condition x Block were not significant ($F < 1.03$, $p > .36$). The nonsignificant three-way interaction, $F(6, 312) = 1.81$, $p = .1$, $\eta_p^2 = .03$, suggests that the results pattern of the reward group did not change between Block 1.1 and Block 1.2. To corroborate this null finding, the performance difference on AX-AY errors and AY-BX errors in the reward condition of the first and second AX40-AY40 block were compared using Bayesian analysis: the Bayes factor BF_{10} was 0.343 for AX-AY errors and 0.220 for AY-BX errors thus providing moderate evidence for the null. That is, the rewarded participants do not seem to have changed their response strategy from Block 1.1 to Block 1.2 (Rouder, Speckman, Sun, Morey, & Iverson, 2009)[20].

[20] We used the preset medium scale parameter of r = .707; using the wide scale parameter (r=1) further reduced the probability of H1.

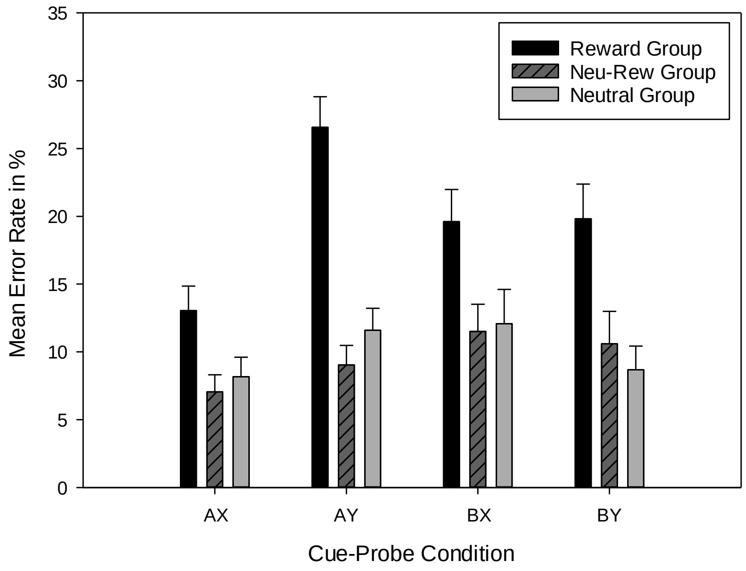


Figure 9. Experiment 2A, Block 1.1/2: Mean error rate in % as a function of cue-probe condition and group. Error bars represent one standard error of the mean.

Error Rates – Transition from Block 1.2 (AX40-AY40) to Blocks 2.1/2 (AX70-AY10). Error rates were entered into a 3 (group: reward, neutral-reward, neutral) x 3 (block: Block 1.2, Block 2.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 10). The three-way interaction was not significant, $F(12, 624) = 0.94$, $p = .5$, $\eta_p^2 = .02$, indicating no significant adjustment to new task conditions within a specific group. But, the visual inspection of Figure 10 seems to suggest that the reward onset in the neutral-reward group enhanced cue usage in the AX70-AY10 blocks compared with the neutral group.

The interaction between block and cue-probe condition, $F(6, 624) = 5.15$, $p < .001$, $\eta_p^2 = .05$, reached significance. T-tests on the interaction between block and cue-probe condition revealed a significant increase in AY errors, $t(106) = 3.96$, $p < .001$, $d = 0.44$, and a significance decrease in AX errors from Block 1.2 to Block 2.1, $t(106) = 3.21$, $p = .002$, $d = 0.28$. The performance difference on AY-BX errors increased from Block 1.2 to Block 2.1, $t(106) = 2.98$, $p = .004$, $d = 0.38$, suggesting an increase in cue maintenance across all groups. BX and BY errors did not differ significantly between Block 1.2 and Block 2.1, both ts < 0.64, both ts > .53, both ds < 0.07. There was no further significant increase / decrease on AX, AY, BX, or BY errors from Block 2.1 to Block 2.2, all ts < 1.62, all ts > .11, all ds < 0.19.

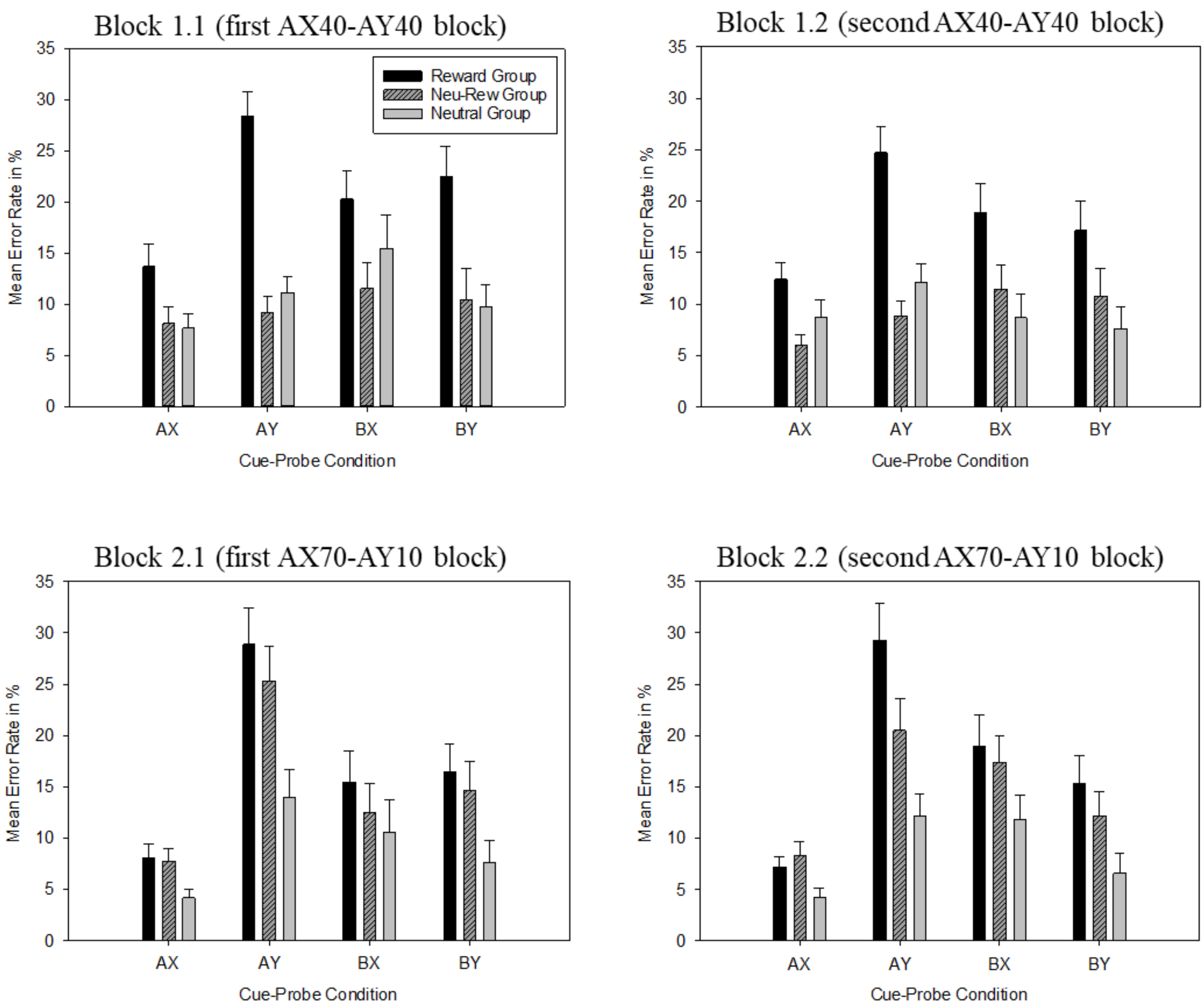


Figure 10: Experiment 2A: Mean error rate in % as a function of group, cue-probe condition and block. Error bars represent one standard error of the mean. For the sake of completeness, the figure also shows the first AX40-AY40 block (Block 1.1) even though it was not included in the analysis.

RT data – Block 1.1/2 (AX40-AY40). Mean median RTs were entered into a 3 (group: reward, neutral-reward, neutral) x 4 (block: Block 1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA.

The analysis revealed a significant main effects of group, $F(2, 104) = 8.41$, $p < .001$, $\eta_p^2 = .14$, reflecting lower RTs in the reward group compared with the neutral-reward group and neutral group. There was also a main effect of cue-probe condition, $F(3, 312) = 24.42$, $p < .001$, $\eta_p^2 = .19$. Participants responded slower to AY trials than to all other trial types (AX trials, $t(106) = 11.47$, $p < .001$, $d = 0.95$; BX trials, $t(106) = 4.65$, $p < .001$, $d = 0.34$; BY trials, $t(106)$

= 5.18, $p < .001$, $d = 0.42$). RTs on BX and BY trials did not differ significantly, $t(106) = 1.13$, $p = .26$, $d = 0.07$. The main effect of block also was significant, $F(1, 104) = 11.68$, $p < .001$, $\eta_p^2 = .1$, with higher RTs in Block 1.1 than in Block 1.2.

No interaction was significant (Group x Block: $F(2, 104) = 0.71$, $p = .49$, $\eta_p^2 = .01$, Block x Cue-probe condition: $F(3, 312) = 1.48$, $p = .22$, $\eta_p^2 = .01$, Group x Cue-probe condition: $F(6, 312) = 1.2$, $p = .31$, $\eta_p^2 = .02$, Group x Block x Cue-probe condition: $F(6, 312) = 0.25$, $p = .96$, $\eta_p^2 = .005$).

RT data – Transition from Block 1.2 (AX40-AY40) to Block 2.1/2 (AX70-AY10). Mean median RTs were entered into a 2 (group: reward, neutral-reward, neutral) x 3 (block: Block 1.2, Block 2.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA.

The interaction between block and cue-probe condition, $F(6, 624) = 6.17$, $p < .001$, $\eta_p^2 = .06$, reached significance. The three-way interaction was not significant, $F(12, 624) = 1.13$, $p = .34$, $\eta_p^2 = .02$.

T-tests on the interaction between block and cue-probe condition revealed a significant decrease in AX RTs, $t(106) = 10.71$, $p < .001$, $d = 0.74$, and AY RTs, $t(106) = 2.03$, $p = .05$, $d = 0.18$, from Block 1.2 to Block 2.1. The performance difference on AY-BX RTs increased from Block 1.2 to Block 2.1, $t(106) = 3.02$, $p = .003$, $d = 0.33$. RTs on B-cue trials also significantly decreased from Block 1.2 to Block 2.1, both *t*s > 4.58, both *p*s < .001, both *d*s > 0.4. There was no further significant increase / decrease in AX, AY, BX, or BY RTs from Block 2.1 to Block 2.2, all *t*s < 1.4, all *p*s > .16, all *d*s < 0.05.

Discussion

In Experiment 2A, we aimed to investigate whether our assumption - reward prospect makes participants use (action-irrelevant) stimulus frequencies for rule preparation - holds true even when cues have never been predictive of the target rule. Moreover, we were interested in examining whether cue maintenance increases (especially in the neutral-reward group as compared to the neutral group) when the predictive value of contextual cues changes from non-predictive (AX40-AY40, action-irrelevant, stimulus-relevant) to highly predictive (AX70-AY10, action- and stimulus-relevant).

As displayed in Figure 9, the reward group made significantly more errors on AY trials than on AX trials already in the AX40-AY40 blocks. The neutral-reward and neutral group showed only descriptively higher error rates on AY trials as compared to AX trials. Moreover, AY errors are higher than BX errors under reward conditions, whereas under neutral conditions, the reverse data pattern was found. This can be taken as further evidence that reward prospect increases proactive control and cue maintenance, whereas under neutral condition, signs of reactive control could be observed. Between-group comparisons revealed generally higher error rates in the reward group as compared to the neutral-reward and neutral group. However, on top of this, error rates in AY trials increased disproportionally, as evidenced by the significant interaction Group x Cue-probe condition. Thus, error rates on AY trials are *especially* increased in the reward group as compared to both the neutral-reward and neutral group. These findings speak to the idea of a reward-induced increased A-cue usage already in the AX40-AY40 blocks where the cues had never been predictive of the required action. Taken together, the results are in line with our assumption that under performance-contingent reward, rigid cue-usage can be caused by the erroneously usage of action-irrelevant stimulus frequencies for rule preparation. The nonsignificant three-way interaction suggests that that the level of cue maintenance of the reward group did not change between Block 1.1 and Block 1.2. This was further confirmed by Bayesian analyses. It thus seems that the rewarded participants did not reduce cue usage from Block 1.1 to Block 1.2 despite repeated error feedback.

The analysis of the transition from the second AX40-AY40 block to the AX70-AY10 blocks demonstrated an increase in cue maintenance across all groups (thus, contrary to our prediction, also in the reward group) from Block 1.2 (second AX40-AY40) to Block 2.1 (first AX70-AY10 block) as indicated by an increase in the performance difference on AY-BX errors/RTs, an increase in AY errors and a decrease in AX errors. It should, however, be noted that this finding has to be interpreted with caution because it may not be the result of an adaptation process but rather the result of cue maintenance (which was already increased in the AX40-AY40 block) now becoming an efficient strategy due to the changing A-cue validity. That is, participants might have kept a formerly maladaptive strategy that then suddenly became adaptive.

At this point, one might wonder why the transition from AX40-AY40 to AX70-AY10 affected error rates only on AX and AY trials even though an increase in cognitive stability is supposed to decrease error rates on BX trials. However, this effect may be counter-acted by the higher frequency of AX trials, making the X-probe following B-cues more erorr prone.

Visual inspection of Figure 10 seems to suggest that the reward onset in the neutral-reward group enhanced cue usage in the AX70-AY10 blocks as compared to the neutral group speaking to the idea of an adaptation process. But this finding must be interpreted with caution because of the nonsignificant three-way interaction. Overall, further research is needed to clarify what exactly happens at the transition from AX40-AY40 to AX70-AY10.

A closer look at the results on RTs (showing faster RTs in all trial types in the reward group as compared to the other groups) evokes the impression that our findings reflect a pure speed-accuracy tradeoff (SAT) rather than motivational effects of reward. The concern of a SAT is not new and has been repeatedly discussed elsewhere (see Chiew & Braver, 2013; Fröber & Dreisbach, 2016a; Hefer & Dreisbach, 2017). The SAT might be especially prominent in the present data because the modified AX-CPT is much more complex than the standard AX-CPT used in previous studies (e.g. Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a). However, we argue that our data reflect a combination of both, a SAT (as indicated by generally decreased RTs and increased error rates) *and* a shift towards cognitive stability (as indicated by especially increased error rates on AY trials). The observed SAT rather supports than undermines the conclusion of a reward-induced increase in proactive control: predicting the upcoming probe(s) and the corresponding response rule results in fast responses at the cost of higher error rates especially on AY trials (see also Chiew & Braver, 2013).[21]

Finally, it is important to discuss increased error rates on BX trials in the reward group. Under reward conditions decreased rather than increased error rates on BX trials are expected. But, in the modified version of the AX-CPT, participants can only prepare the response rule with cue-onset but must await probe presentation for response selection. Thus, participants may prepare the non-target rule after the presentation of the B-cue but the presentation of X/XX-probe(s) on BX trials may still trigger the retrieval of the target rule which is highly associated to the frequent X/XX probe(s). Consequently, the preparation of the relatively unpracticed non-target rule may be weaker than the learnt (and frequently reinforced) association between the X/XX probe(s) and the target rule (see also Hefer & Dreisbach, 2016, 2017). Increased error rates on BX trials may also be the effect of a SAT which elicit higher error rates on all cue-probe conditions. Critically, however, if error rates are higher on AY than on BX trials, we can speak of a reward-induced increased cue maintenance and proactive control. Conversely, lower error rates on AY than on BX trials would speak to the idea of reduced cue maintenance and reactive control.

To summarize, the results of Experiment 2A support our assumption that performance-contingent reward leads to an overestimation of action-relevance of solely stimulus-predictive context information.

[21] We would like to thank an anonymous reviewer for directing our attention to this issue.

Note, however, that we should not draw premature conclusions from here because the results could be evoked by the written instructions (see the method section for the exact instruction). Wenke, Gaschler, and Nattkemper (2007) observed that instructions can induce bindings between stimulus and response features even without prior execution of the task. And in Experiment 2A, the written instruction strongly emphasized the AX-target rule (as it is usually done in any AX-CPT). Moreover, it is highly likely that the target and non-target rules are represented in different formats, an effect probably further encouraged by the instructions. This is because the AX rule specifies two specific SR-rules, namely for “AX” and “AXX”. By contrast, the AY rule has to be represented in a more abstract format, like “A-one probe” and “A-two probes”. Consequently, the results of the AX40-AY40 blocks may result from misleading instructions and/or from the different representational format of the two rules. These issues will now be addressed one after another in the following experiments.

Experiment 2B

In Experiment 2B the instruction was modified such that it now equally emphasized the AX-target response rule and AY non-target response rule. Moreover, this time only two groups of participants (a reward and a neutral group) were included. The decision was driven by the reasoning that our main research questions can be answered by the comparison of a reward and neutral control group. The neutral-reward group would have only provided further evidence about the typical reward effect which has already been shown in many studies.

Method

Participants. A total of 64 undergraduate students from the University of Regensburg participated for course credit. 63 participants were included in the final data analysis (42 female, 21 male, mean age = 22.81 years, *SD* = 2.55, range 19 - 31). One participants of the neutral group had to be excluded due to an error rate of 100% on BX trials in the AX70-AY10 block. An error rate of 100% can be interpreted in terms the participant did not comply with the instructions. 31 participants were assigned to the neutral group, and 32 participants to the reward group, respectively. Participants had no prior knowledge about reward availability. All participants signed informed consent and were debriefed after the session.

Apparatus, Material and Procedure. The apparatus material and procedure was exactly the same as in Experiment 2A, except for two modifications. (1) This time, only two groups of participants (reward vs. neutral) worked through the experiment. Participants assigned to the reward group had the chance to win one point on each trial for fast and correct responses. As an additional incentive, participants were informed that those three participants with the highest score would get an Amazon voucher (first place 20€, second and third place 10€ each). (2) The instruction was modified such that it now equally emphasized the AX-target response rule and AY non-target response rule. Despite this modification, the AX-target rule remains a specific rule whereas the AY-non-target rule remains abstract:

> "[…] If the cue A is followed by one X, then please press the down-arrow key.
> If the cue A is followed by two XX, then please press the up-arrow key.
> If the cue A is followed by any one letter, then please press the up-arrow key.
> If the cue A is followed by any two letters, then please press the down-arrow key […]"

Data preprocessing and Design. Data preprocessing was identical to Experiment 2A. Comparable to Experiment 2A, the AX40-AY40 block (Block 1.1/2) and AX70-AY10 block (Block 2.1/2) were again split into two halves, each. Again, a 2 (group: reward, neutral) x 2 (block: Block1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors design was used to analyze the AX40-AY40 blocks.

To investigate whether participants adjust to new task conditions, a 2 (group: reward, neutral) x 3 (block: Block 1.2, Block 2.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors design was used. Comparable to Experiment 2A, we will focus on AX and AY errors, the ratio of AY and BX errors, and hypothesis-relevant interactions. A more detailed report of results on error rates can be found in the Supplemental Materials.

Results

Error Rates – Block 1.1/2 (AX40-AY40). Error rates were entered into a 2 (group: reward, neutral) x 2 (block: Block1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 11). The interaction between group and cue-probe condition approached significance, $F(3, 183) = 2.58$, $p = .055$, $\eta_p^2 = .04$. Visual inspection of Figure 11 suggests that this marginal interaction may be due to the interaction AY/BX x Group already observed in Experiment 2A, which in fact turned out to be significant, $F(1,61) = 5.86$, $p = .02$. This can be taken as a sign of increased proactive control under reward condition (leading to relatively higher error rates on AY compared with BX trials) and signs of increased reactive control in the neutral condition (leading to relatively higher error rates on BX than on AY trials). Note however, that the higher order interaction Group x Cue-Probe-Condition just failed significance, which technically does not allow for this analysis. In addition, visual inspection of Figure 11 suggests comparable error rates on AX and AY trials within the neutral group. To corroborate this null finding, AX and AY errors in the neutral condition of the AX40-AY40 blocks were compared using Bayesian analysis: the Bayes factor BF_{10} was 0.191 for the first AX40-AX40 Block and 0.191 for the second block (Rouder et al., 2009).

Thus, the changed instruction reduced the proactive usage of the A-cue in the neutral group (which even shows signs of reactive control as indicated by relatively higher error rates on BX than on AY trials), but the reward group still showed signs of increased cue maintenance.

Comparable to Experiment 2A, the nonsignificant three-way interaction, $F(3, 183) = 0.21$, $p = .89$, $\eta_p^2 = .003$, suggests that the results pattern of the reward group did not change between Block 1.1 and Block 1.2. To corroborate this null finding, the performance difference on AX-AY errors and AY-BX errors in the reward condition of the first and second AX40-AY40 block were compared using Bayesian analysis: the Bayes factor BF_{10} was 0.326 for AX-AY errors and 0.199 for AY-BX errors thus providing moderate evidence that the reward group did not change their response strategy (Rouder et al., 2009).

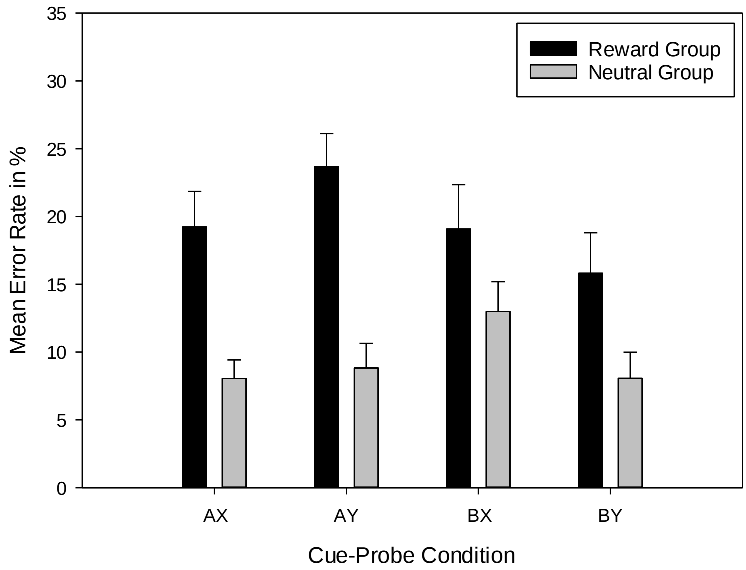


Figure 11. Experiment 2B, Block 1.1/2: Mean error rate in % as a function of group and cue-probe condition. Error bars represent one standard error of the mean.

Error Rates – Transition from Block 1.2 (AX40-AY40) to Block 2.1/2 (AX70-AY10). Error rates were entered into a 2 (group: reward, neutral) x 3 (block: Block 1.2, Block 2.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 12). The interaction between block and cue-probe condition was significant, $F(6, 366) = 4.2$, $p < .001$, $\eta_p^2 = .06$. The three-way interaction was far from significance, $F(6, 366) = 0.58$, $p = .75$, $\eta_p^2 = .01$.

Error rates on AX trials significantly decreased, $t(62) = 4.9$, $p < .001$, $d = 0.34$, and error rates on AY trials significantly increased, $t(62) = 2.98$, $p = .004$, $d = 0.28$, from Block 1.2 to Block 2.1. In addition, the performance difference on AY-BX errors increased from Block 1.2 to Block 2.1, $t(62) = 2.92$, $p = .005$, $d = 0.43$, suggesting an increase in cue maintenance across both groups. Error rates on BX and BY trials did not significantly increase/decrease, both *t*s < 1.44, both *p*s > .16, both *d*s < 0.18. There was no further significant increase/decrease in AX, AY, BX, or BY errors from the Block 2.1 to Block 2.2, all *t*s < 1.08, all *p*s > .29, all *d*s < 0.06.

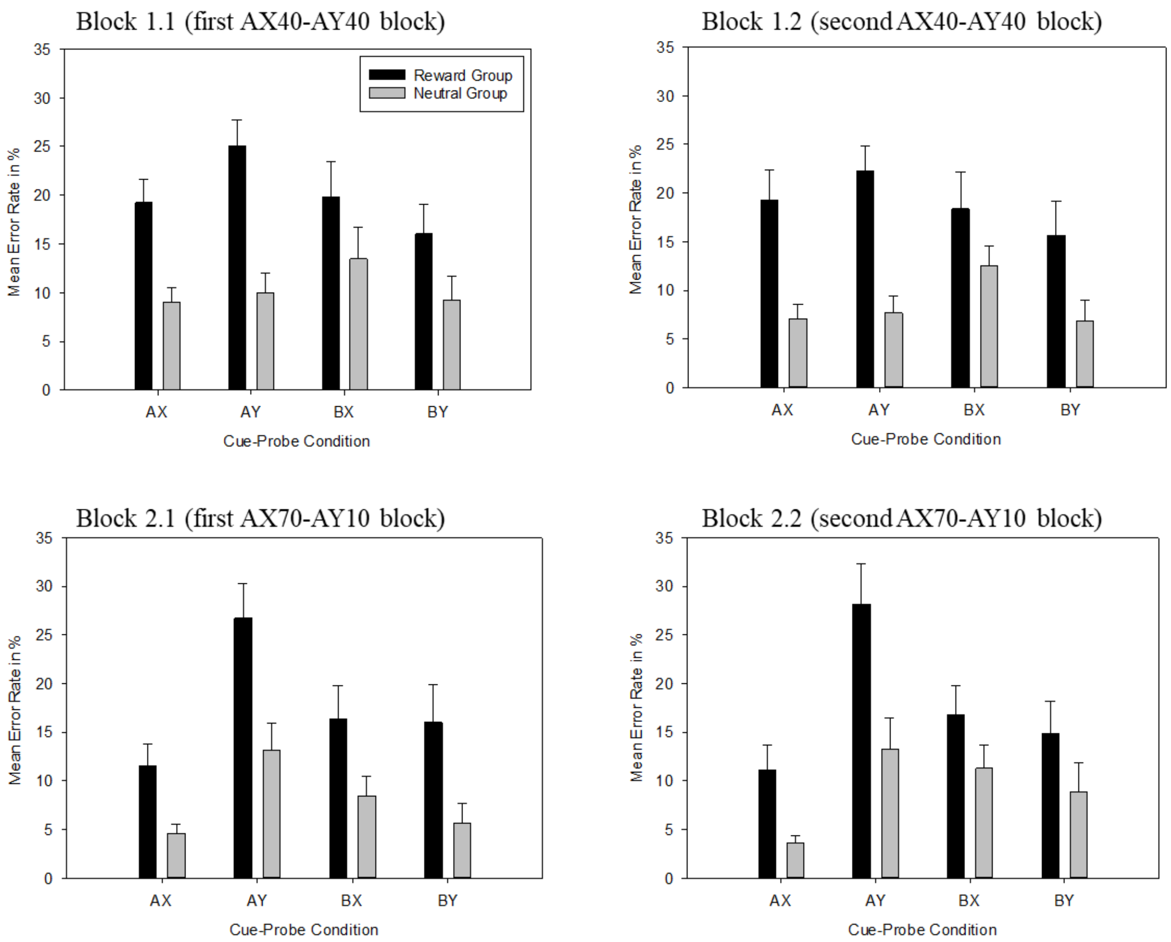


Figure 12. Experiment 2B: Mean error rate as a function of group, cue-probe condition and block. Error bars represent one standard error of the mean. For the sake of completeness, the figure also shows the first AX40-AY40 block (Block 1.1) even though it was not included in the analysis.

RT data – Block 1.1/2 (AX40-AY40). RTs were entered into a 2 (group: reward, neutral) x 2 (block: Block 1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA.

There was a significant main effect of group, $F(1, 61) = 33.64$, $p < .001$, $\eta^2_p = .36$, with faster RTs in the reward group than in the neutral group. There was also a main effect of cue-probe condition, $F(3, 183) = 13.91$, $p < .001$, $\eta^2_p = .19$. Participants responded significantly slower to AY trials relative to AX trials, $t(62) = 6.72$, $p < .001$, $d = 0.59$, relative to BX trials, $t(62) = 4.14$, $p < .001$, $d = 0.3$, and relative to BY trials, $t(62) = 6.26$, $p < .001$, $d = 0.42$. RTs on BX and BY trials did not differ significantly, $t(62) = 1.65$, $p = .1$, $d = 0.11$. The main effect of block did not reach significance, $F(1, 61) = 2.63$, $p = .11$, $\eta^2_p = .04$.

The interaction between group and cue-probe condition was significant, $F(3, 183) = 4.32$, $p = .01$, $\eta^2_p = .07$. The interaction between group and block, $F(1, 61) = 0.67$, $p = .41$, $\eta^2_p = .01$, between block and cue-probe condition, $F(3, 183) = 0.66$, $p = .58$, $\eta^2_p = .01$, and the three-way interaction, $F(3, 183) = 0.61$, $p = .61$, $\eta^2_p = .01$, did not reach significance.

Within-group comparisons showed higher RTs on AY trials than on AX within both groups, both *t*s > 4.92, both *p*s < .001, both *d*s > 0.72. This AX-AY performance difference was comparable for the reward and neutral group as indicated by a non-significant interaction contrast (Group x AX/AY, $F(1, 61) = 3.13$, $p = .08$). The significant interaction contrast Group x AY/BX, $F(1, 61) = 4.9$, $p = .03$, showed a higher AY-BX performance difference for the reward group than for the neutral group, supporting the hypothesis of reward-induced cognitive stability.

Between-group comparisons on the interaction between group and cue-probe condition showed lower RTs in the reward group compared with the neutral group in all cue-probe conditions, all *t*s > 4.12, all *p*s < .001, all *d*s > 1.05.

RT data – Transition from Block 1.2 (AX40-AY40) to Block 2.1/2 (AX70-AY10). RTs were entered into a 2 (group: reward, neutral) x 3 (block: Block 1.2, Block 2.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA.

The interaction between block and cue-probe condition, $F(6, 366) = 5.54$, $p < .001$, $\eta^2_p = .08$, reached significance. The three-way interaction, $F(6, 366) = 0.82$, $p = .55$, $\eta^2_p = .01$, was not significant.

T-tests on the interaction between block and cue-probe condition revealed a significant decrease in RTs on AX and BX trials, and a significant increase in RTs on AY trials from Block 1.2 to Block 2.1, all *t*s > 2.21, all *p*s < .03, all *d*s > 0.16, suggesting an increase in cue maintenance across both groups. The performance difference on AY-BX RTs also increased from Block 1.2 to Block 2.1, $t(62) = 3.32$, $p = .002$, $d = 0.47$. RTs on BY trials did not significantly decrease from Block 1.2 to Block 2.1, $t(62) = 1.09$, $p = .28$, $d = 0.1$. There was a further acceleration observable from Block 2.1 to Block 2.2 only on AX trials, $t(62) = 2.75$, $p = .008$, $d = 0.13$.

Discussion

In Experiment 2B we modified the instructions to avoid emphasis on the AX target rule. This led to equal error rates in AX and AY trials in the neutral group as indicated by the Bayesian analysis. The neutral group showed rather signs of reactive control as indicated by relatively higher error rates on BX than on AY trials. But in the reward group, again *descriptively* increased error rates on AY trials as compared to AX trials can be found already in the AX40-AY40 blocks and relatively higher error rates on AY as compared to BX trials (as indicated by the marginally significant interaction Group x Cue-probe condition). The higher performance difference on AY-BX RTs in the reward group as compared to the neutral group supports the idea of a reward-induced cognitive stability already in the AX40-AY40 block.

Even though the AX-AY performance difference within the reward group was less dramatic than in Experiment 2A (please compare Figure 9 and 11), participants still *tended* to use the higher frequency of the X-probe to prepare for the X-rule even though the Y-rule was equally probable. Please note that this effect was only nearly significant. Comparable to Experiment 2A, the performance difference on AX-AY errors and AY-BX errors did not change within the reward group from Block 1.1 to Block 1.2 thus providing support for the idea that rewarded participants did not adapt their response strategy throughout the AX40-AY40 block despite repeated error feedback.

The analyses of the transition from the second AX40-AY40 to the AX70-AY10 blocks showed that both groups adjusted to the new task conditions in terms of an increase in cue maintenance from Block 1.2 to Block 2.1 as evidenced by an increase in AY errors/RTs, a decrease in AX errors/RTs, and an increase in the performance difference on AY-BX errors/RTs. Once again, this finding has to be interpreted with caution because it is still not entirely clear whether participants really shift towards increased cue maintenance or whether they continued using an already established control strategy which simply became efficient in the AX70-AY10 block (whereby AY errors automatically increased, and AX errors decreased).

We have now shown that reward makes participants especially vulnerable to biased instructions. But even with unbiased instructions as in Experiment 2B, we found signs for increased cue usage under reward when the cue is not yet predictive of the upcoming rule. This marginally significant effect should finally completely disappear when we make the AY rule as specific as the AX rule.

Experiment 2C

In Experiment 2C the modified task instruction of Experiment 2B was used and the Y-probe in AY trials was always the letter Y. The Y-probe in BY trials remained a variable and could be replaced by any letter except for the letter A and X and Y (comparable to Experiments 2A and 2B). Based on Braver et al. (2007) who argue that cue maintenance is only likely in situations where cueing information is predictive of the upcoming stimulus or the required action, even rewarded participants should no longer use the A-cue for rule preparation in AX40-AY40 blocks. The question will be, whether participants under reward will then be able to adapt to changed context condition, namely when the cue validity changes from nonpredictive (AX40-AY40) to predictive (AX70-AY10).

Method

Participants. A total of 70 undergraduate students from the University of Regensburg participated for course credit. 66 participants were included in the final data analysis (51 female, 15 male, mean age = 23.17 years, *SD* = 3.16, range 19 - 33). A boxplot analysis revealed that one participant of the reward group and one participant of the neutral group had to be excluded due to extremely high error rates (49.82% vs. $M_{reward\text{-}group}$= 13.5%, and 49.35% vs. $M_{neutral\text{-}group}$= 10.4%). Two further participants of the neutral group were excluded. One due to an error rate of 100% on BX trials in the AX70-AY10 block, the other one due to extremely high overall RTs (1228 ms vs. $M_{neutral\text{-}group}$= 613 ms). 32 participants were assigned to the neutral group, and 34 participants to the reward group, respectively. Participants had no prior knowledge about reward availability. All participants signed informed consent and were debriefed after the session.

Apparatus, Material and Procedure. The apparatus was identical to Experiments 2A and 2B. The material and procedure was exactly the same as in Experiment 2B, except that the Y-probe in AY trials was always the letter Y. Instructions were the same as in Experiment 2B with the exception that the Y-rule was explicitly introduced. Identical to Experiment 2B, a neutral control group and a reward group worked through the AX-CPT.

Data preprocessing and Design. Data preprocessing was identical to Experiments 2A and 2B. To investigate whether rewarded participants still show preparatory behavior in the AX40-AY40 blocks, a 2 (group: reward, neutral) x 2 (block: Block1.1/2) x 4 (cue-probe condition:

AX, AY, BX, BY) mixed factors design was used. Moreover, a Bayesian analysis will be reported because of the predicted null hypothesis. To investigate whether participants adjust to new task conditions, a 2 (group: reward, neutral) x 3 (block: Bock 1.2, Block 2.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors design was used. Again, we will focus on AX and AY errors, the ratio of AY and BX errors and hypothesis-relevant interactions. A more detailed report of results on errors rates can be found in the Supplemental Materials.

Results

Error Rates – Block 1.1/2 (AX40-AY40). Error rates were entered into a 2 (group: reward, neutral) x 2 (block: Block1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA. The interaction Group x Cue-probe condition did not reach significance, $F(3, 192) = 1.23$, $p = .3$, $\eta_p^2 = .02$. The remaining interactions also did not reach significance, all Fs < 1.17, all ps > .28.

To corroborate this null finding, AX and AY errors in the reward condition of the first and second AX40-AY40 blocks were compared using Bayesian analysis: the Bayes factor BF_{10} was 0.18 for the first AX40-AX40 Block and 0.19 for the second block thus providing substantial evidence for the null hypothesis (Rouder et al., 2009).

Error Rates – Transition from Block 1.2 (AX40-AY40) to Block 2.1/2 (AX70-AY10). Error rates were entered into a 2 (group: reward, neutral) x 3 (block: Bock 1.2, Block 2.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 13).

The interaction between block and cue-probe condition, $F(6, 384) = 6.82$, $p < .001$, $\eta_p^2 = .1$, was significant. The three-way interaction just reached significance, $F(6, 384) = 2.12$, $p = .05$, $\eta_p^2 = .03$.

T-tests on the significant interaction between block and cue-probe condition revealed a significant decrease in AX errors, $t(65) = 5.02$, $p < .001$, $d = 0.48$, and a significant increase in AY errors from Block 1.2 to Block 2.1, $t(65) = 3.2$, $p = .002$, $d = 0.3$. Error rates on B-cue trials did not change significantly from Block 1.2 to Block 2.1, both ts < 1.73, both ps > .09, both ds < 0.19. There was no significant increase / decrease in AX, AY, BX, or BY errors observable from Block 2.1 to Block 2.2, all ts < 1.23, all ps > .2, all ds < 0.13. There was a marginally significant increase in the performance difference on AY-BX errors from Block 1.2 to Block 2.2, $t(65) = 1.79$, $p = .08$, $d = 0.2$, further suggesting an increase in cue maintenance across both groups.

The increase in AY errors and the increase in the performance difference on AY-BX errors was mainly driven by the reward group as indicated by the results of the three-way interaction: within-group comparisons showed a significant increase in AY errors, $t(33) = 3.04$, $p = .005$, $d = 0.37$, a significant decrease in AX errors, $t(33) = 4.09$, $p < .001$, $d = 0.64$, and a significant increase in the difference on AY-BX errors, $t(33) = 2.29$, $p = .03$, $d = 0.38$, from Block 1.2 to Block 2.1. The neutral group instead showed an increase in the performance difference on AY-BX errors from Block 2.1 to Block 2.2, $t(31) = 2.18$, $p = .04$, $d = 0.35$, suggesting a delayed adaptation to new task conditions. Between-group comparisons showed a higher performance difference on AY-BX errors in the reward group compared with the neutral group only in Block 2.1, $t(64) = 3.34$, $p = .001$, $d = 0.82$.

As displayed in Figure 13, *both* groups showed comparable error rates on AX and AY trials in the AX40-AY40 blocks as indicated by the nonsignificant interaction between group and cue-probe condition and the Bayesian analysis. Both groups, but especially the reward group adjusted to new task conditions as evidenced by a significant increase in AY errors, a significant decrease in AX errors, and a significant increase in the AY-BX performance difference from the second AX40-AY40 to the first AX70-AY10 block.

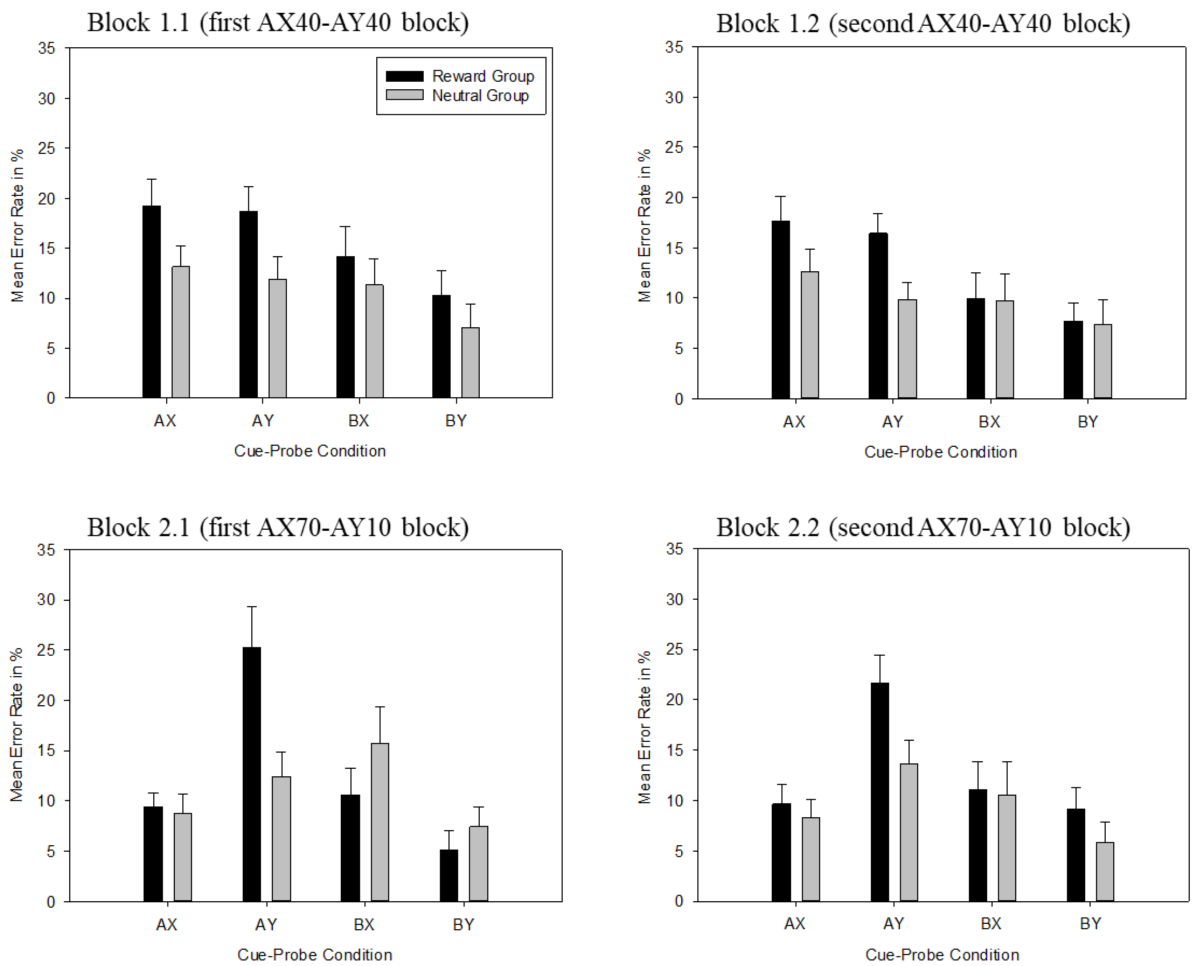


Figure 13. Experiment 2C: Mean error rates in % as a function of group, cue probe condition and block. Error bars represent one standard error of the mean. For the sake of completeness, the figure also shows the first AX40-AY40 block (Block 1.1) even though it was not included in the analysis.

RT data – Block 1.1/2 (AX40-AY40). RTs were entered into a 2 (group: reward, neutral) x 2 (block: Block 1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA. The main effect of group reached significance, $F(1, 64) = 10.62$, $p = .002$, $\eta_p^2 = .14$, with lower RTs in the reward group compared with the neutral group. There was a significant main effect of cue-probe condition, $F(3, 192) = 54.91$, $p < .001$, $\eta_p^2 = .46$. Participants responded slower to AY trials relative to BX trials, $t(65) = 11.43$, $p < .001$, $d = 1.13$ and relative to BY trials, $t(65) = 8.95$, $p < .001$, $d = 0.92$. RTs on BX and BY trials, $t(65) = 0.93$, $p = .36$, $d = 0.05$, and on AY and AX trials, $t(65) = 1.38$, $p = .17$, $d = 0.11$, did not differ significantly. The main effect of block was not significant, $F(1, 64) = 0.3$, $p = .58$, $\eta_p^2 = .005$.

No interaction reached significance (Block x Group: $F(1, 64) = 0.37$, $p = .54$, $\eta_p^2 = .006$, Cue-Probe Condition x Group: $F(3, 192) = 0.78$, $p = .51$, $\eta_p^2 = .01$, Block x Cue-probe condition: $F(3, 192) = 0.68$, $p = .57$, $\eta_p^2 = .01$, Group x Block x Cue-Probe Condition: $F(3, 192) = 0.24$, $p = .87$, $\eta_p^2 = .004$).

RT data – Transition from Block 1.2 (AX40-AY40) to Block 2.1/2 (AX70-AY10). RTs were entered into a 2 (group: reward, neutral) x 3 (block: Block 1.2, Block 2.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA.

The interaction between block and cue-probe condition, $F(6, 384) = 10.99$, $p < .001$, $\eta_p^2 = .15$, reached significance. Participants accelerated AX RTs from Block 1.2 to Block 2.1, $t(65) = 8.22$, $p < .001$, $d = 0.4$. RTs on AY trials, $t(65) = 1.58$, $p = .12$, $d = 0.14$, and on B-cue trials, both *t*s < 0.19, both *p*s > .85, both *d*s < 0.02, did not differ significantly between Block 1.2 and Block 2.1. There was a significant increase in the performance difference on AY-BX RTs only from Block 1.2 to Block 2.2, $t(65) = 2.82$, $p = .006$, $d = 0.37$. There was a further significant acceleration on AX trials observable from Block 2.1 to Block 2.2, $t(65) = 4.32$, $p < .001$, $d = 0.19$. There was no further increase/decrease on AY, BX, and BY trials from Block 2.1 to Block 2.2, all *t*s < 1.5, all *p*s > .14, all *d*s < 0.14.

The interaction Group x Block x Cue-Probe Condition was not significant, $F(6, 384) = 1.75$, $p = .11$, $\eta_p^2 = .03$.

Combined analysis of the rewarded groups across all three experiments. To further strengthen our overall interpretation that the level of cue maintenance under reward conditions decreases with decreasing predictive value of cuing information, we ran a final analysis comparing the rewarded groups across all three experiments. To this end, a 3 (experiment: reward groups of experiment 2A, 2B, and 2C) x 2 (block: Block 1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors design was used.

The analysis of error rates revealed a significant interaction between experiment and cue-probe condition, $F(6, 294) = 4.08$, $p < .001$, $\eta_p^2 = .08$. The reward group of Experiment 2A made significantly more errors on AY than on AX trials, $t(34) = 5.51$, $p < .001$, $d = 1.11$. The reward group of Experiment 2B shows only descriptively higher AY than AX errors, $t(31) = 1.42$, $p = .17$, $d = 0.31$. The reward group of Experiment 2C shows comparable error rates on

AX and AY trials, $t(33) = 0.29$, $p = .77$, $d = 0.06$. From this final analysis, we can conclude that the degree of cognitive stability decreased across the three experiments.

The analysis of RTs also revealed a significant interaction between experiment and cue-probe condition, $F(6, 294) = 11.08$, $p < .001$, $\eta_p^2 = .18$.

Discussion

In Experiment 2C we used the modified instruction of Experiment 2B and no longer replaced the Y-probe in AY trials by any other letter from the alphabet. That is, the A-cue was no longer predictive of the upcoming stimulus or the required action. This time, the interaction between group and cue-probe condition no longer reached significance indicating no group differences on AX/AY trials in the AX40-AY40 blocks. Thus, the A-cue was no longer used by the reward group to prepare a specific response rule in advance. This is in accordance with Braver et al. (2007) who argue that a shift toward increased cognitive stability in terms of enhanced cue maintenance does not occur in situations where contextual cues are not predictive of upcoming stimuli or required actions.

Comparable to Experiment 2A and 2B, both groups showed a significant increase in cue maintenance from Block 1.2 to Block 2.1 (increase in AY errors, decrease in AX errors/RTs, increase in the performance difference on AY-BX errors) as evidenced by the significant interaction between cue-probe condition and block. This time, the finding can clearly be interpreted as an adaptation process to changed task conditions because there were no signs of increased preparation of a specific response rule in the AX40-AY40 blocks. This adaptation process was mainly driven by the reward group: The three-way interaction was significant indicating an adaptation process to changed task conditions especially within the reward group (decrease in AX errors, increase in AY errors, and a significant increase in the difference on AY-BX errors from Block 1.2 to Block 2.1). The neutral group instead did not increase cue maintenance from Block 1.2 to Block 2.1. Quite the contrary, it showed increasing BX errors from Block 1.2 to Block 2.1 and a negative AY-BX performance difference in Block 2.1 (higher error rates on BX than on AY trials, see Figure 13) which could be a hint for the failure to increase cue maintenance. But this finding must be interpreted with caution because the increase in BX errors is only visible for Block 2.1 and could be an artefact. Therefore, it might be better to speak of a delayed adaptation to new task conditions. This assumption is supported by the finding of a higher performance difference on AY-BX errors in the reward group as compared to the neutral group only in Block 2.1. It could be that the modifications made in Experiment 2C (changed instruction, Y-probe in AY trials was no longer a variable) supported especially the reward group to efficiently engage in cue maintenance when needed. The neutral group instead might have needed more time to recognize the changed stimulus frequencies (and consequently changed rule frequencies) in the AX70-AY10 blocks because now the change in stimulus frequencies was less obvious as compared to Experiment 2A and 2B (where the Y-probe was a variable). Moreover, the neutral group might have been less focused on identifying predictive contextual information as compared to the reward group.

The results of Experiment 2C further support the idea that reward prospect does not prevent the adaptation from non-predictive to predictive cues. This fits into the overall picture that reward increases the usage of any potentially relevant contextual information.

General Discussion

Previous research demonstrated that the prospect of performance-contingent reward enhances cognitive stability (cue maintenance) at the cost of reduced flexibility to adjust to new context conditions (Hefer & Dreisbach, 2017). The purpose of the present study was to investigate the possible mechanisms that might underlie this observed maladaptive perseveration.

Experiments 2A, 2B, and 2C were designed to investigate the assumption that reward makes participants vulnerable to mistake stimulus frequencies for rule frequencies. Experiment 2A showed that in the context of reward prospect, participants already use the A-cue to prepare for the specific X-rule even though the A-cue at the beginning was equally predictive of the (abstract) Y-rule. Experiment 2B was a replication of the former experiment with a less biased task instruction where we again found a bias towards stronger A-cue triggered X-rule preparation under reward conditions. Only when the Y-probe in AY trials was always the letter Y, in Experiment 2C, the reward group no longer showed signs of increased cue usage. Thus, the degree of cognitive stability decreased across the three experiments, that means with decreasing predictive value of cueing information. In sum, the results of Experiment 2A, 2B, and 2C allow us to identify the process underlying a maladaptive and perseverative cue usage as it was found in the study of Hefer and Dreisbach (2017): Reward prospect promotes cue usage as long as the cue is predictive of the upcoming stimulus (Experiment 2A and 2B) or the upcoming stimulus and required action (Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a; Hefer & Dreisbach, 2016; 2017). In other words, reward prospect encourages the selective usage of any information that might be relevant for preparatory behavior. Remarkably, results of Experiment 2A and 2B in the AX 40-A40 blocks confirm that this holds true even when the cue had never been predictive of the response rule and thus cue usage had never been experienced as adaptive in this context.

The findings of the transition from the second AX40-AY40 block to AX70-AY10 blocks must be interpreted with caution because they may not be the result of an adaptation process but rather the result of cue maintenance (which was already increased in the AX40-AY40 block) now becoming an efficient strategy due to the changing task conditions. Moreover, contrary to our prediction the reward group and neutral group of Experiment 2A and 2B adjusted to new task conditions to the same extent. Only the reward group of Experiment 2C (and descriptively the neutral-reward group of Experiment 2A) showed a special increase in cue maintenance supporting the idea of an adaptation process. The present findings are a good starting point for future research to investigate the dynamic of the reward effect.

Reward and Error Feedback

In our previous study, we found that rigid cue usage comes along with an inflexibility to adapt to changed task conditions (change from AX70-AY10 to AX40-AY40) despite repeated error feedback on AY trials (Hefer & Dreisbach, 2017). Here, the inflexibility again can be seen in the inability to use the repeated error feedback (rewarded participants of Experiment 2A and 2B did not adapt their response strategy within AX40-AY40 blocks) for adaptation. This is even more surprising, given the existing evidence that the error related negativity (ERN) is typically found to be enlarged under reward conditions (Maruo, Schacht, Sommer, & Masaki, 2016; Stürmer, Nigbur, Schacht, & Sommer, 2011). Reward thus should make participants more sensitive to error feedback. Note, however, that there are methodological differences between the reviewed studies and the present study regarding the applied paradigm (e.g., Simon task vs. AX-CPT) or the reward conditions (e.g., chance to win or lose money in the reward block in Stürmer et al. (2011) vs. no loss of money in the present study).

So, given that we always provided explicit feedback after each trial, the question remains why participants under reward conditions are so sensitive to (seemingly) predictive context information but rather insensitive to error feedback. One possible reason might be that reward prospect also increases risk taking behavior. For instance, Xue, Lu, Levin, and Bechara (2011) demonstrated that participants were more risk-seeking after losing a gamble than after winning a gamble. Assuming that losing a gamble is comparable to making an error, error feedback in the present study could have increased risk-taking and consequently the acceptance of error feedback. Moreover, the small reward magnitude of 0.03 € in Experiment 2A / one point in Experiment 2B and 2C on each trial could have further increased risk-taking behavior (cf. Bornovalova et al. (2009) who showed that participants were less risky at higher as compared to lower levels of reward/loss magnitude). But that remains speculation, because after all, the present data are not suitable to decide whether reward prospect does or does not increase error awareness. If reward does not affect error awareness, participants might have simply continued using the A-cue for rule preparation (resulting in AY errors). If reward does increase error awareness, participants should have adjusted their control strategy and consequently increased their effort. In the AX-CPT, however, increasing effort means increasing cue maintenance for preparatory activity which in turn also results in AY errors. Thus, the only conclusion we can make is that under reward conditions participants do not shift away from persistent cue usage despite repeated error feedback.

Manipulation of Reward and Speed

One might wonder whether our results are evoked by the prospect of performance-contingent reward or the RT-deadline (or a combination of both). In fact, this is a general problem in all studies that manipulate performance contingent reward because the contingency typically is expressed in terms of fast and correct responses (e.g. Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a; Hefer & Dreisbach, 2016, 2017). And because the provision of reward that is given non-contingent on performance (and even for errors) has opposite effects and reduces proactive control and stability (e.g. Fröber & Dreisbach, 2014, 2016a), there is no easy solution to this issue. However, we strongly assume that a reward manipulation that does not stress speed but only accuracy would lead to an overly cautious response strategy (slow, error avoidant). On the other side, a pure speed strategy without any negative consequences for committed errors would simply increase the error rate overall but should not interact with trial type. In order to keep participants motivated (which is the whole point of providing performance contingent reward) to follow the speed instructions we need to stress both, speed and accuracy. That is, the characteristic data pattern of decreased RTs (on all cue-probe conditions) and increased error rates overall and especially so on AY trials may be the result of a reward *and* speed manipulation. In any case, we think that reward and speed are strongly related in our everyday live (e.g., no one is rewarded for good work if it takes too much time) which is why the manipulation of reward *and* speed also bears some ecological validity.

Cognitive Stability and Flexibility

At this point, one might ask whether we should still argue that reward-induced increased cognitive stability comes at the costs of reduced flexibility. In our former study (Hefer & Dreisbach, 2017) we found that participants under reward conditions did not adapt when the cue validity changed from predictive to non-predictive (AX70-AY10 to AX40-AY40).

Experiment 2C of the present study, however, shows that participants especially under reward (but also under neutral) condition actually are able to adapt from non-predictive to predictive cues (from AX40-AY40 to AX70-AY10). However, as stated above, the inflexibility in our opinion shows in the inability to adapt to the repeated error feedback as shown in Experiments 2A and 2B. But still, the question arises whether we need to speak of two concepts (stability vs. flexibility) when the main findings can be best summarized under the assumption of persistent cognitive stability in the context of reward irrespective of whether it is adaptive or not: persistent cue maintenance explains the delayed decrease in cue maintenance in our former study (Hefer & Dreisbach, 2017), it explains the usage of any potentially relevant information in Experiment 2A and 2B, and it explains the adaptation from non-predictive to predictive cues in Experiment 2C. However, we argue that in order to fully capture our findings both concepts are needed because both modes of control are associated with complementary benefits and costs. While cognitive stability supports goal-shielding and anticipating behavior, it may incur a cost in terms of perseverative behavior. Conversely, while cognitive flexibility enhances flexible set shifting, it may incur a cost in terms of increased distractibility (cf. Goschke & Bolte, 2014). Moreover, cognitive stability and flexibility are associated with different brain areas (prefrontal cortex and striatum) as well as different dopamine activity systems (e.g., Cools & D'Esposito, 2011). In other words, the exclusive reference to the concept of cognitive stability would explain the rigid cue usage but it would not cover the reduced sensitivity to feedback from the environment. At this point, it is inevitable to think of Braver's DMC especially since we refer to cue maintenance as the as the *proactive* maintenance and usage of contextual information. Proactive and reactive control are - as well as cognitive stability and flexibility - associated with different costs and benefits and different temporal dynamics and location of brain activity which speaks to the idea of a dual-mode system rather than a single-mode system (Braver, 2012). Taken together, the present results provide evidence that reward prospect modulates the balance between stability and flexibility favoring a stable mode of control at the cost of decreased flexibility in terms of reduced sensitivity to feedback from the environment.

Further Evidence for the Downside Effect of Reward

Taken together, the present study contributes to a broad research field that investigates the influence of performance-contingent reward on cognition including attention (e.g., Pessoa & Engelmann, 2010; Shomstein & Johnson, 2013), memory (e.g., Miendlarzewska, Bavelier, & Schwartz, 2016), task switching (e.g., Fröber & Dreisbach, 2016b; Kleinsorge & Rinkenauer, 2012), response inhibition (e.g., Boehler, Schevernels, Hopf, Stoppel, & Krebs, 2014), or interference effects (e.g., Chiew & Braver, 2016; for a review see Botvinick & Braver, 2015; Yee & Braver, 2018). While most of these studies observed performance benefits in the context of reward, the present study highlights its detrimental effects (for a review see Bonner, Hastie, Sprinkle, & Young, 2000). There exists further evidence that indicates possible downsides of reward in terms of maladaptive perseverative behavior: For instance, Krebs, Boehler, and Woldorff (2012) observed performance costs in incongruent Stroop trials in which words were semantically related to the reward predicting ink colors. Anderson, Laurent, and Yantis (2012) demonstrated that a stimulus feature (e.g., color) associated with reward captures attention thereby influencing performance even when reward is no longer available (see also Anderson, Laurent, & Yantis, 2011; Hickey, Chelazzi, & Theeuwes, 2010). It thus seems that previously reward-associated stimuli can interfere with target selection even when they have become completely irrelevant to the task (for a review see Anderson, 2013; Chelazzi, Perlato, Santandrea, & Della Libera, 2013). These results can be summarized under the term of *value-driven attentional capture*, a form of attentional control in which stimuli (previously) associated with reward have a direct influence on attention priority through learning (Anderson et al., 2012). Please note that the reviewed studies focus on how performance is influenced by a particular subset of stimuli (e.g., a certain color) associated with reward availability. The detrimental effect of reward in terms of maladaptive perseveration was also observed in studies that investigated – comparable to the present study - the effect of reward on cue usage. Lynn and Shin (2015) used a Posner-cueing paradigm and demonstrated that a previously reward-associated and valid cue can still capture attention even when specific instructions are provided that the cue has no value anymore. In sum, the reviewed studies all express negative side-effects of performance-contingent reward. And they once again show that whenever reward is used to guide attention and action one should keep possible and unwanted consequences in mind.

Conclusion

The research presented here brought up two main findings: (1) It shows that reward prospect increases the usage of any predictive context information, be it action relevant or not. And (2) it shows that the reward-induced cue usage persists until the cuing information loses any predictive information.

Acknowledgment

We thank Lena Breu, Nadine Gonsior, and Luisa Schmucker for data collection.

Compliance with Ethical Standards

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

Conflict of Interest: Carmen Hefer declares no conflict of interest. Gesine Dreisbach declares no conflict of interest.

The research presented here was supported by a grant from Deutsche Forschungsgemeinschaft DFG: DR 392/7-1 to Gesine Dreisbach.

Appendix

Table A1. Mean error rates in % and SDs of Experiment 2A.

Group	Cue-Probe Condition	Block 1.1		Block 1.2		Block 2.1		Block 2.2	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Reward group	AX	13.7	12.9	12.4	9.7	8.1	7.9	7.2	6
	AY	28.4	14	24.7	14.7	28.9	20.6	29.3	21
	BX	20.3	16	18.9	16.4	15.5	17.8	18.9	18
	BY	22.5	17.4	17.1	17.2	16.4	16.3	15.4	16.1
Neutral-Reward group	AX	8.1	9.6	6	6.2	7.8	7.1	8.3	7.9
	AY	9.2	9.5	8.9	8.4	25.3	20.1	20.5	18.9
	BX	11.6	15.4	11.5	13.8	12.5	16.6	17.4	15.3
	BY	10.4	18.8	10.8	16.1	14.6	17.3	12.2	14.5
Neutral group	AX	7.6	8.4	8.7	10.4	4.2	4.8	4.3	5.2
	AY	11.1	9.2	12.1	11.4	14	15.8	12.2	12.8
	BX	15.5	19.4	8.7	13.6	10.5	19.5	11.8	14.6
	BY	9.7	13.1	7.6	12.4	7.6	12.8	6.6	11.8

Table A2. Reaction times in ms and SDs of Experiment 2A.

Group	Cue-Probe Condition	Block 1.1		Block 1.2		Block 2.1		Block 2.2	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Reward group	AX	540	147	523	117	462	84	458	81
	AY	668	140	661	132	685	134	679	160
	BX	611	205	571	214	530	173	513	170
	BY	574	179	557	206	507	178	508	172
Neutral-Reward group	AX	671	215	653	186	470	113	461	97
	AY	839	194	803	159	639	131	662	126
	BX	804	325	745	343	530	184	504	162
	BY	804	450	726	280	511	161	519	169
Neutral group	AX	630	154	631	138	542	101	540	101
	AY	824	193	801	147	853	167	849	158
	BX	712	307	656	216	620	240	635	213
	BY	682	252	639	224	619	242	632	233

Table A3. Mean error rates in % and SDs of Experiment 2B.

Group	Cue-Probe Condition	Block 1.1		Block 1.2		Block 2.1		Block 2.2	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Reward group	AX	19.2	13.8	19.2	17.5	11.5	12.9	11.2	14.5
	AY	25.1	14.9	22.3	14.2	26.7	20.1	28.1	23.5
	BX	19.8	20.3	18.4	21.8	16.4	19.2	16.8	17
	BY	16	17.2	15.6	19.8	16	21.8	14.8	18.6
Neutral group	AX	9.1	8.4	7.1	8.7	4.6	5.1	3.6	3.9
	AY	10	11	7.7	9.9	13.2	15.1	13.3	17.7
	BX	13.5	18	12.5	11.2	8.5	11.4	11.3	13.4
	BY	9.3	13.3	6.9	12	5.6	11.6	8.9	16.5

Table A4. Reaction times in ms and SDs of Experiment 2B.

Group	**Cue-Probe Condition**	**Block 1.1**		**Block 1.2**		**Block 2.1**		**Block 2.2**	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Reward group	AX	522	120	512	111	474	96	451	89
	AY	623	112	599	104	664	156	646	160
	BX	476	134	461	121	416	86	437	114
	BY	471	105	469	139	437	86	424	84
Neutral group	AX	724	167	714	158	626	123	616	113
	AY	911	251	845	244	850	222	897	290
	BX	839	415	828	382	738	351	735	341
	BY	793	466	728	346	701	334	683	222

Table A5. Mean error rates in % and SDs of Experiment 2C.

Group	**Cue-Probe Condition**	**Block 1.1**		**Block 1.2**		**Block 2.1**		**Block 2.2**	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Reward group	AX	19.2	15.8	17.6	14.4	9.5	7.6	9.7	11.1
	AY	18.7	14.4	16.5	11.4	25.3	23.7	21.7	16.1
	BX	14.1	18	9.9	15.3	10.6	15.6	11	16.5
	BY	10.3	14.3	7.7	10.7	5.1	11.1	9.2	12.4
Neutral group	AX	13.2	12	12.6	12.6	8.8	10.5	8.3	10
	AY	11.9	12.9	9.9	9.6	12.4	13.8	13.7	13.2
	BX	11.3	14.7	9.8	14.8	15.7	20.6	10.5	18.8
	BY	7	13.4	7.4	13.4	7.4	11.4	5.9	11.4

Table A6. Reaction times in ms and SDs of Experiment 2C.

Group	**Cue-Probe Condition**	**Block 1.1**		**Block 1.2**		**Block 2.1**		**Block 2.2**	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Reward group	AX	593	126	571	127	517	116	500	114
	AY	618	141	603	122	611	132	619	132
	BX	459	118	459	116	442	134	438	100
	BY	451	114	444	108	443	122	448	136
Neutral group	AX	695	182	698	193	606	141	571	119
	AY	711	115	694	118	726	149	730	158
	BX	529	205	541	189	566	205	520	139
	BY	564	243	568	235	564	264	527	206

STUDY 3

The volatile nature of positive affect effects: opposite effects of positive affect and time on task on proactive control

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Hefer, C., & Dreisbach, G. (2018). The volatile nature of positive affect effects: opposite effects of positive affect and time on task on proactive control. *Psychological research*, 1-10. https://doi.org/10.1007/s00426-018-1086-4

Abstract

There is growing evidence suggesting that positive affect promotes cognitive flexibility at the cost of increased distractibility and decreased proactive control. Regarding the latter effect, some studies revealed inconsistent or even diverging findings casting doubt on the reliability of this observation. Recently, it has been shown that motivation can counteract positive affect effects. Here, the authors provide evidence for another factor that opposes positive affect effects, namely time on and experience with a task. To this end, the well proven AX-continuous performance task (AX-CPT) was used. Three groups of participants received three blocks of the AX-CPT with a positive affect manipulation (positive group) or neutral affect manipulation (neutral group) or alternating affect blocks (mixed group: pos-neut-pos). Results confirmed the positive affect effect associated with decreased proactive control in the positive and mixed group as compared to the neutral group. Most importantly, all groups showed an increase in proactive control with increasing time on task supporting our prediction that time on task is another factor opposing the positive affect effect. The results thus reveal the sensitivity of the positive affect effect to strategic influences developed with increasing experience with the given task. Implications for future research on the interplay of mild positive affect and cognitive control will be discussed.

Introduction

In the last decades it has repeatedly been shown, that positive affect plays a central role in modulating cognitive control (for reviews see Dreisbach & Fischer, 2012; Goschke & Bolte, 2014; Van Steenbergen, 2015). While most studies show increased cognitive flexibility under positive affect (e.g., Dreisbach, 2006; Dreisbach & Goschke, 2004; Fröber & Dreisbach, 2012; Rowe, Hirsh, & Anderson, 2007; Wang, Chen, & Yue, 2017; Yang & Yang, 2014, Zwosta, Goschke, Hommel, & Fischer, 2013), there are some findings that do not fit into this general picture (e.g., Bruyneel et al., 2013; Chiew & Braver, 2014; Sacharin, 2009, chapter 3). These inconsistent findings might have different causes: (1) Hidden and so far unknown moderator variables that counteract the positive affect effect, (2) methodological differences and undefined concepts (e.g., different mood/affect induction procedures, underspecified concepts like "flexibility", c.f., Sacharin, 2009) and/or (3) the effect in question does not exist and findings in the literature are based on a publication bias (Francis, 2012; Giner-Sorolla, 2012). Here, we aim to address issues 1 and 2 by identifying yet another moderator of positive affect effects and by confining our hypotheses to one specific facet of cognitive flexibility. In particular, we will show that positive affect reduces proactive control, i.e. the preparatory usage of context information (see Dreisbach, 2006; Fröber & Dreisbach, 2012; 2014; van Wouwe, Band, & Ridderinkhof, 2011), thereby enabling higher flexibility in response to unexpected events. Moreover, we will show that time on task increases proactive control even under positive affect thereby diminishing the positive affect effect.

With proactive control, we refer to the dual mechanism of control (DMC) framework by Braver (2012; Braver, Gray, & Burgess, 2007) where he differentiates between two distinct modes of control: namely proactive and reactive control. Proactive control refers to the maintenance of goal-relevant information allowing for response preparation in advance. Reactive control refers to a "just-in-time" control that has to be activated by an appropriate trigger. Critically, proactive control depends on the availability of valid cues about upcoming events. From there, it follows that a reduced usage of proactive control impairs performance on valid, that is, expected events. Conversely, reduced proactive control has *beneficial effects* on *unexpected* invalid effects. That is, the cognitive flexibility to adjust to unexpected events can in fact be a consequence of reduced cue usage.

There is much evidence that positive affect reduces proactive control (e.g. Dreisbach, 2006; van Wouwe, Band, & Ridderinkhof, 2011), but positive affect also improves creative problem solving (e.g., Estrada, Young, & Isen, 1994) and verbal fluency (e.g., Phillips, Bull, Adams, & Fraser, 2002), reduces response conflict (e.g., Xue et al., 2013) and switch costs (e.g., Wang et al., 2017), and broadens the scope of attention (e.g., Rowe et al., 2007). Most studies summarized these findings under the general term of increased cognitive flexibility under positive affect. However, the problem here is that the concept of flexibility in terms of creative problem solving very likely differs from the concept of flexibility in terms of reduced proactive control. That is, the Remote Associates Test for example (see Estrada, Young, & Isen, 1994; Bolte, Goschke, & Kuhl, 2003) may measure a different component of cognitive flexibility as compared to task switching paradigms (see for example Wang et al., 2017) or the AX-Continuous Performance Task (see for example Dreisbach, 2006; Fröber & Dreisbach, 2014). That is, cognitive flexibility is a diversified concept and, to shed light on the affective modulation of cognitive flexibility, it is important to clearly state what kind of cognitive flexibility a researcher has in mind. For example, Sacharin (2009) distinguishes between associative flexibility (e.g., creating new associations, originality) and regulative flexibility (e.g., adjusting to changes in the environment) . Here, we will focus on regulative flexibility and, to further narrow the concept, on cognitive flexibility as a consequence of *reduced* proactive control. As stated above, proactive control depends on the availability of valid pre-information. Accordingly, affective modulation of proactive control has been mainly shown in cuing paradigms like the spatial cuing paradigm and cued task switching (Fröber & Dreisbach, 2012) or the AX continuous performance task (AX-CPT, Dreisbach, 2006; Fröber & Dreisbach, 2014; van Wouwe, Band, & Ridderinkhof, 2011) the latter of which we will now explain in more detail as it will also be used in the present experiment.

The AX-CPT (Servan-Schreiber, Cohen, & Steingard, 1996) is a context processing task that is ideally suited to measure the relative contribution of proactive and reactive control. In this task sequences of letters are presented: the first letter is called cue, the last letter is called probe. There are two types of cue (A or B), and two types of probe (X and Y) resulting in four different cue-probe conditions: AX, AY, BX, and BY trials. The cue B and the probe Y stands for any letter of the alphabet expect the letter A and X. Whenever the A-cue is followed by an X-probe, the trial is a target trial requiring a target response (e.g., left key press). Whenever the A-cue is not followed by the X-probe (AY trials), or the cue is not an A but a B (BX, BY trials), the trial is a nontarget trial requiring a nontarget response (e.g., right key press). Thus, only on AX target trials, participants have to give a target response, otherwise a nontarget response. Critically, AX sequences occur with 70% frequency which makes the A-cue highly informative about the occurrence of the X-probe. All remaining nontarget trials occur with 10% frequency each. Critically, in the AX-CPT, a high level of proactive control typically impairs performance in AY trials: The stronger the A-cue is maintained, the higher the costs if this expectation is hurt, that is, when the A-cue is not followed by the expected X-probe, but by the unexpected Y-probe. At the same time, proactive control improves performance on B-cue trials because the B-cue unambiguously indicates a nontarget trial requiring a nontarget response (irrespective of the following X- or Y-probe). Decreased proactive control (as typically found under positive affect) on the other side typically improves performance on AY trials due to the weaker preparation of the target response, thus reducing response conflict when the Y-probe appears (c.f., Fröber & Dreisbach, 2014). Reactive control typically increases RTs on BX trials (rather than error rates on BX trials) because less maintenance of the B-cue reduces the preparation of the nontarget response. Consequently, the B-cue information has to be retrieved from the episodic memory which is a time-consuming process (for corresponding arguments see Chiew & Braver, 2017; Paxton, Barch, Storandt, & Braver, 2006).

Several studies using the AX-CPT have consistently shown, that mild positive affect reduces proactive control as evidenced by reduced AY error rates (Dreisbach, 2006; Fröber & Dreisbach, 2014; van Wouwe et al., 2011). Most importantly, for the questions we aim to address here, Fröber and Dreisbach (2014) have shown how easily this positive affect effect can be overridden. In their study, participants under positive affect showed clear signs of increased proactive control as evidenced by an abrupt increase in AY errors as soon as they were informed that they would be rewarded for fast and correct responses (for further evidence how reward increases proactive control, see also Chiew & Braver, 2013, 2014, Fröber & Dreisbach, 2014, 2016; Hefer & Dreisbach, 2016, 2017; Locke & Braver, 2008). This was taken as evidence that the effects of mild positive affect can be trumped by motivation. Given that in any experiment, motivational states might fluctuate between participants and across time, motivation is thus one possible moderator that might counteract positive affect effects (unbeknownst and unintended by the experimenter). However, what does not fit into this picture is that Chiew and Braver (2014) also investigating the effects of positive affect and reward on proactive control in the AX-CPT, from the beginning found slightly increased proactive control under positive affect (in the absence of reward). A closer look at their methods section might explain this finding: Participants in their study first worked through 200 baseline trials before the positive affect induction was administered. 200 trials are ten times more baseline trials than Fröber and Dreisbach used in their study (2014; 20 trials). We assume that increasing experience with the AX-CPT overrides the positive affect effect because participants under neutral affect conditions learn quickly that a proactive strategy in the AX-CPT task is actually rewarding in itself. The proactive control strategy is rewarding because the cues are highly valid. That is, only on (the rare 10%) AY trials, the proactive response preparation is maladaptive whereas in all other trials, such a proactive strategy allows for fast and correct performance. Consequently, we assume that participants with more experience with the task (200 trials in Chiew and Braver's study) might have gotten immune against any affective modulation that reduces proactive control. This would also converge with Paxton, Barch, Storandt, and Braver (2006) who observed increased proactive control in the AX-CPT as a pure time on task effect even under neutral affect conditions.

Here, we aim to test the hypothesis that time on and experience with the AX-CPT gradually increases proactive control thereby opposing the usually observed reduced proactive control under positive affect. To this end, we employed three groups of participants: a neutral control group, a positive group in which positive affect was induced in all blocks, and a mixed group in which positive affect was induced in Block 1 and Block 3 but not in Block 2 (which was a neutral block). We expected to find reduced proactive control in the positive affect groups as compared to the neutral affect group. This should show in reduced error rates on AY trials. Moreover, we expected that proactive control in all groups would increase with time on task. That is, also in the positive group, we expect to find increasing AY errors over the course of the three blocks. The mixed group (pos-neut-pos) was introduced to rule out a possible alternative interpretation of our predicted effect for the positive group: An increase in proactive control in the positive group over the course of the experiment could be ascribed to a habituation effect to the positive affect induction (and not to the experience with the AX-task). Presenting a neutral block in between should prevent this affective habituation. If we still find signs of increased proactive control with increasing time on task in this mixed group, this would be a clear sign that experience with the task increases proactive control and thus diminishes the positive affect effect.

Method

Participants

A total of 61 undergraduate students from the University of Regensburg participated for course credit. One participant of the neutral group was excluded because of his particularly slow performance ($M = 632$ ms vs. $M_{\text{remaining participants}} = 319$ ms). Thus, 60 participants were included in the final data analysis (20 participants per group, 40 female, 20 male, mean age = 22.95 years, *SD* = 3.35, range 19 - 37). All participants signed informed consent and were debriefed after the session.

Apparatus

Participants were tested individually in a lab at the University of Regensburg. The experiment was run on a Dell PC computer with a 17-inch monitor. The experiment was presented using E-Prime 2.0 (Psychology Software Tools, Sharpsburg, PA, USA). Responses were collected using a QWERTZ keyboard, with the “y” and “m” keys serving as response keys. AX target trials required a target response ("y"- or "m"- key which was counterbalanced across participants). AY, BX, and BY nontarget trials required the respective nontarget response ("m"- or "y"-key).

Material and procedure

The letters A and X served as A- cue and X-probe respectively. All other letters from the alphabet (except for A and X) could serve as B-cue and Y-probe. In between cue and probe, three distractor letters were presented that again could be any letter from the alphabet beside A and X. Half of the participants had to answer with a target response (e.g., left key) to the AX-sequence and with a nontarget response (e.g., right key) to all other sequences (AY, BX, BY). The other half of participants received the reversed response mapping. AX sequences occur with 70% frequency, the nontarget trials AY, BX, and BY with 10% frequency each. Cue and probe were presented in magenta (Arial font, bold, size 28), distractor letters were presented in black (Arial font, bold, size 24). All letters were presented centered on a gray background. Like in previous studies (Fröber & Dreisbach, 2012, 2014) ten different pictures of the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1999) were used for a given affect (positive, neutral) manipulation because they are known to evoke affective reactions even with short presentation durations (Codispoti, Bradley, & Lang, 2001; see the Appendix A for the numbers of the specific IAPS pictures as well as valence and arousal values). Pictures were presented centered on a gray background in a landscape format, adjusted to a size of 800 x 600 pixels. Pictures did not repeat on consecutive trials.

Each trial started with the presentation of one neutral or positive IAPS picture (400 ms) followed by a blank screen (100 ms). The cue appeared for 300 ms, followed by a blank screen (200 ms) and three distractor letters (each for 300 ms). After another blank screen (200 ms), the probe letter was presented and remained on the screen until a response was given. Responses were followed by a visual feedback message for 1500 ms. The German word Richtig! ("Correct") in blue was presented after correct responses, the German word Falsch! ("Wrong") in red was presented after incorrect responses. Before the next trial an inter-trial interval (blank screen, 500ms) was presented (see Figure 14). Participants were informed that the cue would be presented only for a short time and that they had to react to the probe.

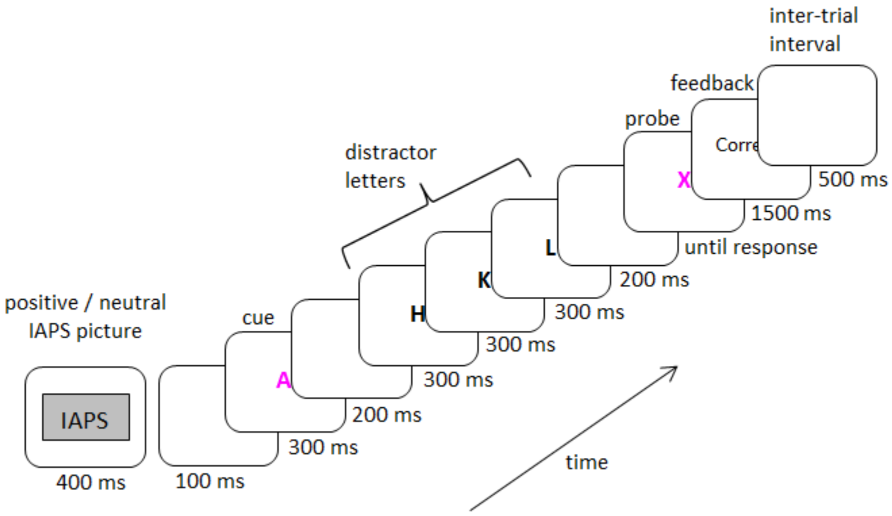


Figure 14. Trial structure of an AX target trial, with one preceding positive vs. neutral IAPS picture.

For each group, the experiment started with written instructions and 20 practice trials (14 AX, 2 AY, 2 BX, 2 BY). All participants were asked to react as quickly and accurately as possible. All groups then received three experimental blocks with a positive or neutral affect manipulation in block 1 (160 trials, 112 AX, 16 AY, 16 BX, 16 BY randomly intermixed), block 2 (160 trials, 112 AX, 16 AY, 16 BX, 16 BY randomly intermixed) and block 3 (80 trials, 56 AX, 8 AY, 8 BX, 8 BY; see also Hefer & Dreisbach, 2017, Experiment 1A). The neutral / positive group received three blocks with a neutral / positive affect manipulation; the mixed group (pos-neut-pos) received three blocks with a positive affect manipulation in Block 1 and 3, and a neutral affect manipulation in Block 2.

To assess if the affect manipulation evoked by the IAPS pictures was successful, subjects' emotional and arousal states were measured at three different points of time: at the beginning of the experiment, after Block 1 and at the end of the experiment. To this end we used the Self-Assessment Manikins (SAM, Bradley & Lang, 1994), a nonverbal method to measure pleasure and arousal on a nine point Likert scale.

Design

To investigate the positive affect effect, we compared the performance of both positive affect groups with the neutral group. To this end, a 4 (cue-probe condition: AX, AY, BX, BY) x 3 (block: 1, 2, 3) x 3 (group: positive, mixed, neutral) mixed factors design was used. Cue-probe condition and block were manipulated within participants, affect was a between participants variable. Error rates (in %) and reaction times (RTs, in milliseconds) served as dependent measures. Note that in the AX-CPT, error rates are usually more diagnostic with respect to the involvement of proactive control because increased proactive control results in generally low RTs but selectively increased AY errors (see also Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014; Hefer & Dreisbach, 2017; Locke & Braver, 2008). Therefore error rates will be presented first.

To check for shifts in valence and arousal states over time a 3 (rating time: at the beginning, after Block 1, at the end) x 3 (group: positive, mixed, neutral) ANOVA was conducted.

Raw data files can be found online here https ://epub.uniregensburg .de/37684.

Results

Valence and arousal measurements

A 3 (rating time) x 3 (group) mixed-factors ANOVA of valence ratings revealed a significant main effect of rating time, $F(2, 114) = 19.46$, $p < .001$, $\eta_p^2 = .25$, as well as a significant interaction between rating time and group, $F(4, 114) = 3.56$, $p = .01$, $\eta_p^2 = .11$. The main effect group did not reach significance, $F(2, 57) = 1.83$, $p = .17$, $\eta_p^2 = .06$. There was a significant decrease of valence rating only from time one (at the beginning) to time two (after Block 1), $F(1, 57) = 27.95$, $p < .001$, 6.7 vs. 5.8. Planned comparisons on the significant interaction revealed significantly higher valence ratings in the positive groups as compared to the neutral group at rating time two (after Block 1), $F(1, 57) = 4.59$, $p = .04$, and three (at the end), $F(1, 57) = 4.71$, $p = .03$ (see Table 4). At the beginning of the experiment, the positive groups showed comparable valence ratings relative to the neutral group, $F(1, 57) = 0.12$, $p = .74$.

A 3 (rating time) x 3 (group) mixed-factors ANOVA of arousal ratings revealed a significant main effect of rating time, $F(2, 114) = 10.38$, $p < .001$, $\eta_p^2 = .15$, indicating a higher arousal level at the beginning of the experiment as compared to at the end of the experiment, $F(1, 57) = 8.42$, $p = .005$, 3.4 vs. 2.6. The main effect group, $F(2, 57) = 0.39$, $p = .68$, $\eta_p^2 = .01$, as well as the interaction did not reach significance, $F(4, 114) = 0.63$, $p = .64$, $\eta_p^2 = .02$.

Table 4. Mean and standard deviation of the valence and arousal ratings as a function of rating time and group.

	Group	Rating time 1		Rating time2		Rating time 3	
		M	*SD*	*M*	*SD*	*M*	*SD*
Valence Rating	Positive group	6.85	1.76	6	1.72	5.6	2.06
	Mixed group	6.65	1.81	6.3	1.52	6.5	1.91
	Neutral group	6.6	1.18	5.2	1.61	4.9	1.83
Arousal Rating	Positive group	2.95	1.39	2.75	1.52	2.45	1.32
	Mixed group	3.6	2.06	2.85	1.76	2.85	2.06
	Neutral group	3.5	1.47	2.85	1.14	2.6	1.19

Preprocessing

For the analysis of performance data practice trials and the first trial of each experimental block were excluded. In addition, error trials were excluded prior to the mean median RT analysis.

Error rate

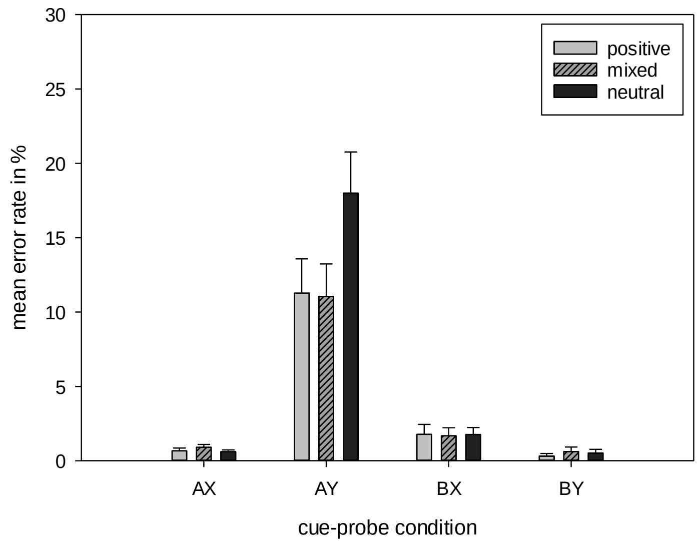
Mean error rates were entered into a 3 (group: positive, mixed, neutral) x 4 (cue-probe condition: AX, AY, BX, BY) x 3 (block: 1, 2, 3) mixed factors analysis of variance (ANOVA). The ANOVA revealed a significant main effect of block, *F* (2, 114) = 7.62, *p* < .001, η_p^2 = .12, and cue-probe condition, *F* (3, 171) = 80.32, *p* < .001, η_p^2 = .58 (see Figure 15). The main effect of group was not significant, *F* (2, 57) = 1.93, *p* = .15, η_p^2 = .06. Overall, error rates significantly increased from block 1 to block 2, *F* (1, 57) = 9.7, *p* = .003, 3% vs. 4.3%. There was no further increase from block 2 to block 3, *F* (1, 57) = 1.94, *p* = .17, 4.3% vs. 5%. Participants made significantly more errors on AY trials than on AX trials, *F* (1, 57) = 84.38, *p* < .001, 13.4% vs. 0.7%, on AY trials than on BX trials, *F* (1, 57) = 76.14, *p* < .001, 13.4% vs. 1.7%, as well as on AY trials than on BY trials, *F* (1, 57) = 87.06, *p* < .001, 13.4% vs. 0.5%.

Critically, the interaction Cue-probe condition x Group, *F*(6, 171) = 2.71, *p* = .02, η_p^2 = .09, as well as Cue-probe condition x Block, *F* (6, 342) = 8.84, *p* < .001, η_p^2 = .13, reached significance. The interaction between block and group, *F* (4, 114) = 0.99, *p* = .42, η_p^2 = .03, and the three-way interaction, *F* (12, 342) = 0.78, *p* = .67, η_p^2 = .03, did not reach significance.

In line with our predictions, planned comparisons revealed significantly decreased error rates on AY trials in the positive affect groups (mixed group: 11.1%, positive: 11.3%) as compared to the neutral group (18%), *F*(1, 57) = 5.25, *p* = .03. The positive groups did not significantly differ from the neutral group in BX errors, *F*(1, 57) = 0.004, *p* = .95, BY errors, *F*(1, 57) = 0.02, *p* = .88, and AX errors, *F*(1, 57) = 0.77, *p* = .39.

Planned comparisons on the significant Cue-Probe Condition x Block interaction showed a significant increase in AY errors from block 1 to block 2, *F*(1, 57) = 10.8, *p* = .002, 9% vs. 14%, indicating a gradual shift toward proactive control with increasing experience with the task across all three groups. There was no further significant increase in AY errors from block 2 to block 3, *F*(1, 57) = 3.38, *p* = .07, 14% vs. 17.3%. There was no significant decrease / increase in AX, BX, and BY errors from block 1 to block 2 (all *F*s < 1.74, all *p*s > .19) or from block 2 to block 3 (all *F*s < 0.24, all *p*s > .63).

Critically for our hypotheses, AY errors increased across all blocks and across all three groups (see Figure 16).



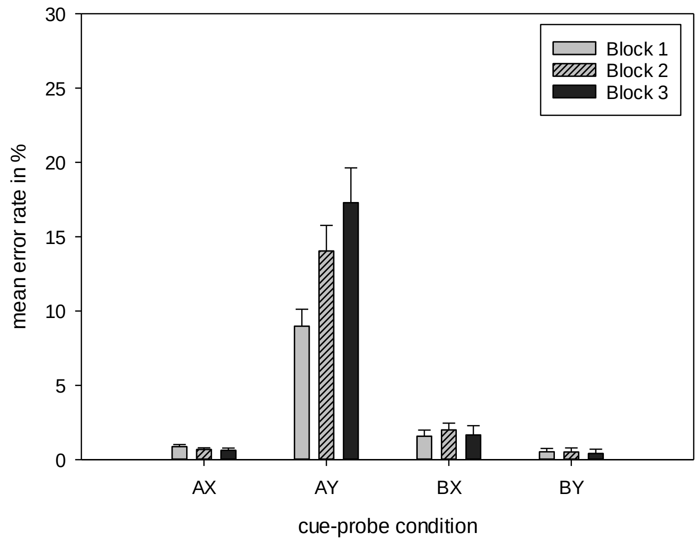


Figure 15. Mean error rates as a function of cue-probe condition (AX, AY, BX and BY) and group (positive, mixed, neutral) (upper panel) and as a function of cue-probe condition and block (lower panel). Error bars represent one standard error of the mean.

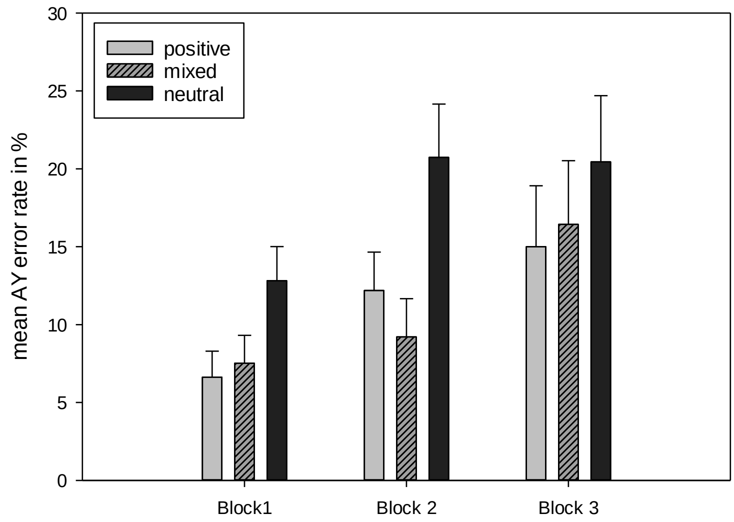


Figure 16. Mean error rates in AY trials as a function of block and group. Error bars represent one standard error of the mean.

RT data

The ANOVA revealed a significant main effect of cue-probe condition, F (3, 171) = 576.08, p < .001, η_p^2 = .91, and block, F (2, 114) = 38.37, p < .001, η_p^2 = .4 (see Figure 17). The interaction between block and cue-probe condition also reached significance, F (6, 342) = 21.81, p < .001,

η_p^2 = .28. The main effect of group, *F* (2, 57) = 0.98, *p* = .38, η_p^2 = .03, the interaction Block x Group, *F* (4, 114) = 1.26, *p* = .29, η_p^2 = .04, the interaction Cue-Probe Condition x Group, *F* (6, 171) = 0.67, *p* = .67, η_p^2 = .02, as well as the three way interaction, *F* (12, 342) = 0.38, *p* = .97, η_p^2 = .01, did not prove reliable. Participants showed the highest RTs on AY trials (506 ms) as compared to AX (357 ms), BX (220 ms) and BY (227 ms) trials (all *F*s > 857.84, all *p*s < .001). RTs significantly decreased from block 1 to block 2, *F* (1, 57) = 38.78, *p* < .001, 351 ms vs. 321 ms, as well as from block 2 to block 3, *F* (1, 57) = 6.54, *p* = .01, 321 ms vs. 311 ms. Planned comparisons on the significant interaction between block and cue-probe condition revealed a significant decrease in RTs from block 1 to block 2 on AX trials, *F* (1, 57) = 9.8, *p* = .003, 366 ms vs. 357 ms, BX trials, *F* (1, 57) = 35.93, *p* < .001, 255 ms vs. 206 ms, and BY trials, *F* (1, 57) = 34.8, *p* < .001, 276 ms vs. 216 ms. From block 2 to block 3 a further speeding was observed only on AX trials , *F* (1, 57) = 6.36, *p* = .01, 357 ms vs. 349 ms, and BY trials, *F* (1, 57) = 14.62, *p* < .001, 216 ms vs. 188 ms. RTs in AY trials did not increase or decrease from block 1 to block 2, *F* (1, 57) = 0.24, *p* = .63, 506 ms vs. 504 ms, or from block 2 to block 3, *F* (1, 57) = 0.36, *p* = .55, 504 ms vs. 508 ms.

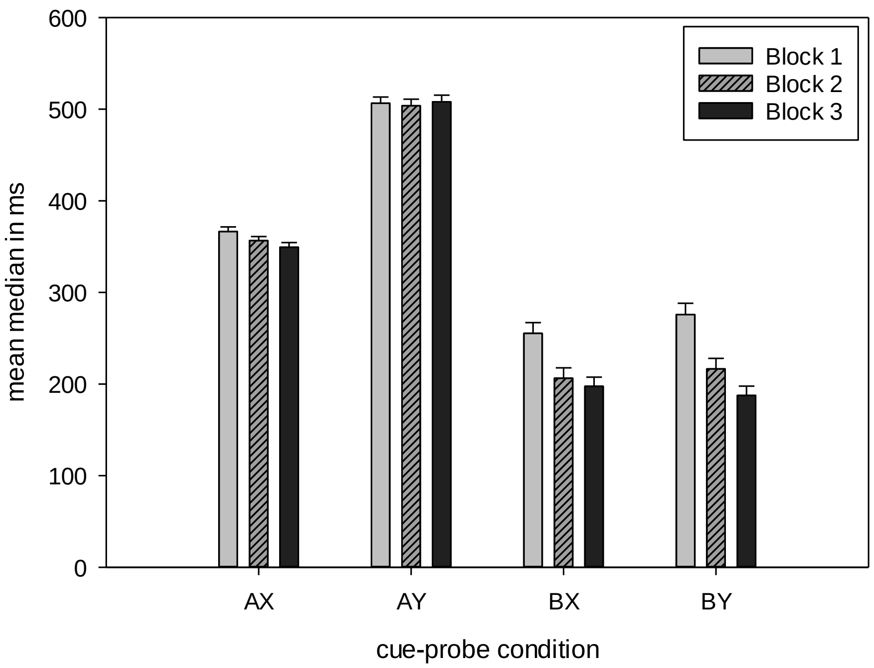


*Figure 17***.** Mean median RTs as a function of cue-probe condition (AX, AY, BX and BY) and block. Error bars represent one standard error of the mean.

General Discussion

In the current study, we aimed to show that the positive affect effect in terms of reduced proactive control is diminished with time on and experience with the AX-CPT. To this end, affect manipulations were employed between and within participants across three experimental blocks. In a nutshell, the significant interaction between cue-probe condition and group in the error data confirms the typical positive affect effect in terms of reduced proactive control resulting in selective accuracy benefits on AY trials in the positive as compared to a neutral group (Dreisbach, 2006; Fröber & Dreisbach, 2014; van Wouwe et al., 2011). Moreover, and most critically, even under positive affect AY errors increased with increasing time on task, suggesting a general increase in proactive control also under positive affect. This cannot be explained by a reduction in positive affect over time. At least the valence ratings speak against this assumption, because compared to the neutral group, the positive affect groups showed a constant level of slightly elevated mood over the course of the experiment. This clearly suggests that it is the specific experience with the task that led participants in the positive affect group to increasingly using the cues for preparation. The results are also in line with research by Compton et al. (2004) as well as Fröber and Dreisbach (2012). There, the authors used a spatial cueing paradigm and observed a reduced cue-validity effect under positive affect conditions which also speaks to the idea of decreased proactive control. These studies as well as the present results can be summarized under the concept of increased regulative flexibility as a consequence of reduced usage of context information.

The results can also be interpreted as meaning that under positive affect the behavior is less dependent on cognitive sets. At the beginning of the experiment, participants assigned to the neutral group rapidly established the cognitive set that the A-cue is highly predictive of the X-probe (and thus the target response) resulting in increased AY errors across the whole experiment. Participants assigned to the positive affect groups instead established this cognitive set more slowly, which is why they show generally lower (but nevertheless constantly increasing) error rates on AY trials as compared to the neutral group. This might have several reasons: Seibert and Ellis (1991) argue that people produce more irrelevant thoughts under emotional (positive or negative) mood states which may hamper the establishment of cognitive sets. Alternatively, and in line with Carver (2003) positive feelings could have served as a safety signal indicating that things are going better than necessary thereby promoting a more explorative behavior and delaying the establishment of cognitive sets.

The significant interaction between cue-probe condition and block demonstrates an increase in AY errors in all three groups suggesting a bias towards stronger cue usage with increasing experience with the task (see also Paxton et al., 2006). In other words, the positive affect manipulation seems to create a lower set point for proactive control but does not impede a gradual adaptation towards more proactive behavior even in the group that received a positive affect manipulation throughout all blocks. The finding of increasing proactive control with increasing task experience is further underlined by a significant speeding especially on AX and BY trials across all groups. In sum, the results show that, without prior knowledge of the task, the amount of proactive control invested in the AX-CPT depends on current affect conditions (here a positive vs. neutral affect manipulation in block 1). With increasing experience, however, the positive affect effect of decreased proactive control fades out in favor of increased proactive control which was independent from the affect manipulation in block 2 (mixed vs. positive affect group). That is, the increase in proactive control under positive affect cannot be ascribed to a habituation of the positive affect manipulation.

AY errors did not increase in the mixed group in Block 2. This might either be due to a sustained positive affect effect (which however is rather unlikely, given that this effect was not found in the positive group) or due to the switch to a new (neutral) picture set. Dreisbach and Goschke (2004) as well as Dreisbach et al. (2005) assumed that positive affect makes participants more vulnerable to distraction by novel information. Applied to the data presented here, such a novelty bias under positive affect might have drawn attention to the newly introduced neutral pictures in Block 2 in the mixed group. This might have come at the expense of reduced cue usage as compared to the positive group. However, given that this effect was not predicted, it should be interpreted with caution.

This newly presented time on task effect under positive affect can explain mixed evidence with regard to positive affect’s influences on cognitive control. The fact, that Chiew and Braver (2014) found – in contrast to our study and Fröber & Dreisbach (2014) - a small *increase* in proactive control under positive affect is – based on our data – probably caused by design differences. We argue that the crucial difference which led to these diverging results might be the varying degrees of experience with the AX-CPT gained *before* the positive affect manipulation was employed. Chiew & Braver (2014) started with a neutral block that promoted the establishment of a proactive control strategy which created the set point from which the proactive control strategy developed (comparable to our neutral group). This resulted in a further (small) increase in proactive control under positive affect. Moreover, based on the results of the mixed group, this once adopted proactive control strategy is not taken back even by a positive affect manipulation. This is taken as evidence that the positive affect effect in terms of reduced reliance on cue usage is very sensitive to strategic influences. That is, not only performance-contingent reward (cf., Fröber & Dreisbach, 2014), but also mere experience with the task, can diminish or even eliminate positive affect effects and pushes participants under positive affect toward a more proactive control strategy. This, in fact, seems to be adaptive because an increase of proactive control over time was observed in all groups suggesting that this control mode is the most intrinsically rewarding and successful strategy at least in this version of the AX-CPT. With respect to the positive affect groups, this means, that the more relaxed control mode can and is easily given up when the experience with that task suggests a better strategy. Critically, this does not necessarily go along with a change in mood.

The increase in proactive control may be surprising considering that proactive control is considered the more effortful strategy (Braver, 2012; Braver et al., 2007) and that participants are interested in minimizing cognitive effort (Kool, McGuire, Rosen, & Botvinick, 2010; but see Inzlicht, Shenhav, & Olivola, 2018). However, proactive control in the AX-CPT by itself is a highly rewarding and efficient strategy. Braver et al. (2007) list several benefits of proactive control that are mostly fulfilled in the AX-CPT and therefore might explain its preference: The cues are highly informative and in 90% of all trials predict the correct response (in all AX, BX and BY trials). Together with the short and constant cue-target-interval, the proactive strategy of always preparing the target response when the A-cue occurs and always preparing the nontarget response when the B-Cue appears might have become automatized with increasing practice in all groups.

We have now identified another moderator that can hamper the effects of mild positive affect on cognitive flexibility: in an earlier study, it was already shown that reward prospect instantaneously eliminates positive affect effects and increases proactive control in the AX-CPT (Fröber & Dreisbach, 2014). Here, we have shown that time on task diminishes the positive affect effect when participants experience that proactive control is the more rewarding strategy in a given task. Both moderators, motivation and time on task, represent a real challenge for the investigation of positive affect effects on cognitive control in the lab. First of all, time on task cannot be avoided but is an inherent feature of any investigation such that positive affect effects might only be observable in the early stages of an experiment. Moreover, the motivational state of participants might fluctuate and depend on the current situation of the participant. It is conceivable, that student subjects who participate between exams might be in a state of higher motivational arousal than participants tested during semester breaks. As long as we are not able to control for these hidden moderators, we run the risk of self-immunizing this kind of research by explaining any absence of an expected positive affect effect with the assumed motivational state of the participants or his/her experience with the task.

It becomes even more complicated: positive affect can be differentiated by more than its source (mild positive affect elicited by positive pictures vs. performance-contingent reward, cf., Fröber & Dreisbach, 2014). For example, there are different mood/affect induction procedures that could influence the effect of positive affect and therefore be another moderator variable: Chiew and Braver (2014) presented a brief positive video clip before the task block and, in addition, on each trial in the positive affect block either a positive or neutral affective IAPS picture (50% each randomly intermixed). Compton et al. (2004) investigated differences in baseline mood state, and Baumann and Kuhl (2005) presented positive, negative, and neutral prime words in random order. Dreisbach (2006) as well as Fröber and Dreisbach (2012, 2014) used affective pictures preceding every trial in a between-groups design. Wang et al. (2017) used affective pictures preceding every trial in a within-groups design. Rowe et al. (2007) let participants listen to music for the happy / sad mood induction, Bruyneel et al. (2013) let participants listen to music while retrieving a positive autobiographical memory. Thus, the studies differ in their mood induction procedure and in investigating sustained (Bruyneel et al., 2013; Compton et al., 2004), transient (Baumann & Kuhl, 2005) or sustained and transient (Chiew & Braver, 2014; Dreisbach, 2006; Fröber & Dreisbach, 2012, 2014; Wang et al., 2017) affect reactions. Please note, that in the present study ten positive IAPS pictures were repeatedly shown over many trials. Although the valence ratings suggest a successful positive affect induction, the number and variability of affective stimuli might be another moderator of positive affect effects.

At this point, it is not possible to say how different affect induction procedures influence the positive affect effect but it is definitively worth taking into account as well as the type of design: within-subject (Baumann & Kuhl, 2005; Chiew & Braver, 2014; Rowe et al., 2007; Wang et al., 2017) or between-subject (Dreisbach, 2006; Fröber & Dreisbach, 2014).

Moreover, arousal is yet another factor that has proven to be influential and also varies with the specific mood or affect induction procedure. As already mentioned, Fröber and Dreisbach (2012) showed decreased proactive control under positive affect but only for low arousal (using positive IAPS pictures with low arousal, as was also done in the study presented here) but slightly increased proactive control under positive affect with high arousal. Accordingly, in the present study we found relatively low arousal ratings (and also used IAPS pictures with low arousal values)[22]. This might even strengthen our interpretation that the

[22] Note that arousal ratings of established affective picture stimuli like the IAPS and subjective arousal ratings from participants before and after the experiment do not necessarily coincide. Moreover, not all studies provide both ratings which makes it even harder to disentangle the respective effects.

arousal level is a moderator influencing the positive affect effect. Likewise, Liu and Wang (2014) demonstrated that low-approach motivated positive affect promotes cognitive flexibility whereas high-approach motivated positive affect promotes perseverance (see also Gable & Harmon-Jones, 2010). This moderator may now explain, why Sacharin (2009) found impaired flexibility under happiness but slightly improved flexibility under relief: happiness was associated with approach, whereas relief was associated with avoidance.

Taken together, there are numerous moderator variables that influence how positive affect modulates cognitive control (level of arousal, level of approach / avoidance). The present study pointed out one further important moderator variable, namely time on and experience with the task.

Conclusion

The study presented here provided further evidence that mild positive affect (with low arousal) reduces the usage of valid cue information and thus proactive control thereby confirming previous findings (Dreisbach, 2006; Fröber & Dreisbach, 2012, 2014; van Wouwe et al., 2011). The results add to the existing literature showing that positive affect can increase cognitive flexibility (provided that this flexibility is a consequence of reduced proactive control). But we also showed that this positive affect effect is diminished with increasing experience with the task. After having shown recently, that increased motivation by rewarding participants for fast and correct responses increases proactive control even under positive affect induction (Fröber & Dreisbach, 2014), we have thus identified another factor that might account for existing discrepancies in the literature when it comes to the affective modulation of cognitive control (c.f., Chiew & Braver, 2014). We would like to emphasize again that our conclusion should not be taken as a free ticket to explain discrepancies away whenever a positive affect effect fails to be replicated. By contrast, the take home message should be that our conclusions are restricted to a specific affect induction (mild positive, low arousal) and a specific paradigm that has proven to be sensitive to the extent of proactive control engagement. The moderator variables identified here and elsewhere might also help to explain the vulnerability of the positive affect effect and should therefore always be considered and – if possible – be controlled in future research.

Appendix A

Numbers of affective picture stimuli (Lang et al., 1999)

Neutral: 7000, 7004, 7006, 7009, 7035, 7040, 7080, 7090, 7175, 7233
Positive: 1440, 1710, 1750, 1920, 2057, 2150, 2260, 2311, 2340, 2530.

The mean ratings for the neutral picture set were valence = 4.99 and arousal = 2.45, and for the positive picture set valence = 7.99 and arousal = 4.55.

Compliance with Ethical Standards

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

Conflict of Interest: Carmen Hefer declares no conflict of interest. Gesine Dreisbach declares no conflict of interest.

Research presented here was supported by a grant from Deutsche Forschungsgemeinschaft DFG: DR 392/7-1 to Gesine Dreisbach.

PART III

GENERAL DISCUSSION

Summary of Findings

The primary goal of the present thesis was to gain insight into the affective and motivational modulation of cognitive control. Results from the studies presented here replicate and extend the existing literature on increased proactive cue usage under performance-contingent reward (cf. Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016a; Hefer & Dreisbach, 2016) and decreased proactive cue usage under positive affect (cf. Dreisbach, 2006; Fröber & Dreisbach, 2012, 2014; van Wouwe et al., 2011) by showing the downside of reward-induced increases in cognitive stability (Studies 1 and 2) and the vulnerability of the positive affect effect to time on task (Study 3). A detailed overview of all experiments, including paradigm, reward motivation and affect manipulation method, and key results, can be found in Table 5.

STUDY 1 replicated the typical findings that reward increases proactive cue usage and demonstrated the persistent nature of this effect. In Experiment 1A, one group of subjects worked through the standard AX-CPT with reward availability in Block 1 and Block 3. As expected, participants showed increases in proactive cue usage from the baseline block to the first reward block. Interestingly, in the nonrewarded Block 2, error rates on AY trials remained high. In Experiment 1B (using the standard AX-CPT) and 1C (using the modified AX-CPT) the predictive value of the A-cue was eliminated (transition from AX-70 to AX-40), such that for successful task performance a reduction in cue usage was beneficial. The results of Experiment 1B show that participants in the reward group (as compared to the neutral group) continued utilizing the cueing information at least in the first half of the AX-40 block. Experiment 1C showed that this rigid cue usage extending into the AX-40 block was especially pronounced when reward was offered continuously. Taken together, these findings show that performance-contingent reward prospect increases cognitive stability at the cost of decreased flexibility as indexed by delayed adaptation to new task (and reward) conditions.

STUDY 2 clarified the mechanism underlying this maladaptive perseveration found in Study 1. To this end, in three experiments using the modified AX-CPT, participants first worked through an AX-40 block followed by an AX-70 block. The results revealed reward-induced increases in proactive cue usage already in the AX-40 block where cues had never been predictive of the required action (Experiment 2A). This finding was replicated in Experiment 2B even though the instruction was modified and now equally emphasized the AX-target rule and AY-nontarget rule. Finally, in Experiment 2C, in which the modified task instruction was used, and the Y-probe was no longer a variable in AY trials, no signs of reward-induced increases in A-cue usage were observed. Taken together, these experiments show that reward prospect encourages the selective usage of any predictive information even when this information is not relevant for the subsequent action.

STUDY 3 was designed to shed light on inconsistent findings regarding the affective modulation of proactive cue usage. Three groups of subjects worked through the standard AX-CPT with a positive and/or neutral affect manipulation. Results supported prior work and showed that positive affect decreases proactive cue usage. However, all groups showed an increase in proactive cue usage with increasing time on task. Thus, time on task might be another factor that counteracts the positive affect effect (as well as motivation as shown by Fröber and Dreisbach, 2014).

In sum, this work replicated the findings that reward motivation and positive affect have diverging effects on cognitive control, and thus can be dissociated from one another[23]. More precisely, results of Studies 1 and 2 answer the question of how to explain reward-induced performance impairments: Reward prospect increases cognitive stability at the cost of decreased cognitive flexibility (in terms of reduced sensitivity to feedback from the environment), resulting in perseverative behavior and, consequently, impaired performance. Thus, results of Studies 1 and 2 provide further support for the idea of a reciprocal relationship between cognitive stability and flexibility. Study 3 points out the vulnerability of the positive affect effect to time on task effects, thereby clarifying inconsistent findings.

To extend beyond the discussions of Studies 1 to 3, some general topics concerning the affective and motivational modulation of cognitive control will be addressed in the following sections.

[23] The first evidence for opposing effects of positive affect and reward motivation on cognitive control comes from studies investigating the conflict adaptation effect (for a review see Dreisbach & Fischer, 2012). The present data confirm these previous results: It thus seems that positive affect can be associated with reduced conflict-driven control (Steenbergen, Band, & Hommel, 2010; see also Steenbergen, Band, Hommel, Rombouts, & Nieuwenhuis, 2015). Performance non-contingent rewards (which may also trigger positive affect without any motivational effects) either reduce sequential conflict adaptation (Steenbergen, Band, & Hommel, 2009; 2012; Yamaguchi & Nishimura, 2019, Experiment 2) or have no effects (Stürmer et al., 2011, Experiment 1), whereas performance-contingent rewards increases sequential conflict adaptation (Braem et al., 2012; Stürmer et al., 2011, Experiment 2).

Table 5. Overview of all experiments from the present thesis.

Study	Experiment	Paradigm	Affect and Reward Manipulation	Results
STUDY 1	Experiment 1A	Standard AX-CPT Baseline Block, 3 AX-70 blocks	1 reward group: Reward availability in Block 1 and 3	Increase in proactive cue usage (increase in AY errors) from the baseline block to Block 1. The reward effect survived the withdrawal of reward in Block 2 (unchanged high AY errors). This was the first evidence for the persistent nature of reward-induced proactive cue usage.
	Experiment 1B	Standard AX-CPT Baseline Block, Transition from AX-70 to AX-40	2 between-subjects groups: neutral vs. reward(reward availability only in the AX-70 block)	Reward prospect increased proactive cue usage (higher AY errors in the reward than neutral group in the AX-70 block) at the cost of a delayed adaptation to changed task conditions (higher AY errors in the reward than neutral group in the AX-40 block, higher AY than AX errors within the reward group at least in the first half of the AX-40 block).
	Experiment 1C	Modified AX-CPT Baseline Block, Transition from AX-70 to AX-40	3 between-subjects groups: neutral vs. Rew-Neut(reward availability only in the AX-70 block) vs. Rew-Rew(reward availability in both blocks)	Reward prospect increased proactive cue usage (higher AY errors in the reward groups than neutral group in the AX-70 block) at the cost of a delayed adaptation to changed task conditions especially in the context of continuous reward (higher AY than AX errors within the Rew-Rew group and higher AY errors in the Rew-Rew group than neutral group in both AX-40 blocks).

Study	Experiment	Paradigm	Affect and Reward Manipulation	Results
STUDY 2	Experiment 2A	Modified AX-CPT Baseline Block, Transition from AX-40 to AX-70	3 between-subjects groups: neutral vs. reward(reward availability in both blocks) vs. neutral-reward(reward availability only in the AX-70 block)	Reward-induced increases in A-cue usage was already present in the AX-40 block even though the A-cue had never been predictive before (higher AY than AX errors within the reward group, higher AY errors in the reward group than the neutral and neural-reward group). All groups showed an increase in cue usage from the AX-40 to the AX-70 block.
	Experiment 2B	Modified AX-CPT Baseline Block, Transition from AX-40 to AX-70 Modified task instruction	2 between-subjects groups: neutral vs. reward group(reward availability in both blocks)	Despite the equal emphasis of the AX target rule and AY nontarget rule in the task instructions, reward-induced increases in A-cue usage were still found in the AX-40 block, albeit less dramatic than in Exp.2A. Again, both groups adjusted to the AX-70 block in terms of an increase in cue maintenance as evidenced by increased AY errors.
	Experiment 2C	Modified AX-CPT Baseline Block, Transition from AX-40 to AX-70 Modified task instruction and Y=Y in AY trials	2 between-subjects groups: neutral vs. reward group(reward availability in both blocks)	No signs of increased cue usage in the AX-40 block when the A-cue was not predictive of required actions or upcoming probe(s). Both groups, but especially the reward group, showed an increase in proactive cue usage from the AX-40 to the AX-70 block.
STUDY 3	Experiment 3A	Standard AX-CPT 3 blocks	3 between-subjects affect groups: neutral vs. positive vs. mixed-positive (pos-neu-pos)	The positive affect effect in terms of decreased proactive cue usage (less AY errors in the positive groups than neutral group) was once again replicated. Time on task diminished the positive affect effect because all groups showed an increase in proactive cue usage over the course of the experiment.

How can Reward-Induced Performance Impairments be Explained?

The results of Studies 1 and 2 clearly show that reward prospect, like positive affect, is associated with complementary costs and benefits: Reward prospect increases cognitive stability at the cost of decreased cognitive flexibility (cf. Müller et al., 2007). Based on these findings, the question raised in the introduction (*How can reward-induced performance impairments be explained?*) can now be (partly) answered. Decreased cognitive flexibility to adjust performance in response to (error) feedback might be one factor explaining reward prospect-induced performance impairments. According to Hommel's (2015) *Metacontrol State Model*, one could argue that reward prospect might have increased the impact of the goal (i.e., obtaining rewards by increased proactive cue usage) to such an extent that all non-goal related alternatives are heavily suppressed, resulting in a stability-favoring control mode at the cost of flexibility.

Previous studies have already shown hints of this stability-increasing and flexibility-decreasing effect of reward motivation: For instance, Fröber and Dreisbach (2014) provided performance-contingent reward on only a subset of 50% of (randomly presented) trials within a given block and found evidence for transient reward effects in terms of faster RTs on reward than nonreward trials. Critically, however, there was no effect of reward availability on error rates in AY trials. This finding suggests that AY errors within a given block were consistently increased, regardless of whether a given trial was rewarded or not. Thus, participants took more time to respond to non-reward trials, presumably because of the absence of a RT deadline, but they showed continuously increased AY errors, which supports the idea of consistently increased proactive control. This finding is in line with Chaillou et al. (2017) who also found reward-induced increases in proactive control in reward and nonreward trials. In a follow-up study, Fröber and Dreisbach (2016a) manipulated reward availability in miniblocks (instead of trial by trial as in their 2014 study). Here, the authors found transient reward effects in terms of higher proactive control in reward as compared to nonreward miniblocks. Nevertheless, despite a decrease in proactive control in nonreward miniblocks, there was still higher proactive cue usage as compared to a baseline block, suggesting a global reward effect. Hefer and Dreisbach (2016), however, did not find any transient reward effects when using the modified AX-CPT. Thus, it might be the case that proactive cue usage cannot be easily switched on and off. This idea contrasts with Braver (2012) who argues that cue maintenance is metabolically costly and should therefore preferentially be engaged in situations with reward availability. Indeed, there is empirical evidence showing that participants engage in effortful proactive control only when reward incentives are provided: Fischer et al. (2018) offered performance-contingent reward in miniblocks (alternating reward vs. no reward miniblocks) in a dual-task situation. Here, fluctuation in proactive control was evidenced by decreased and increased dual task interference corresponding to the current reward condition. This transient reward effect speaks to the idea that participants can in fact voluntarily switch between task shielding (proactive control) and task relaxation (reactive control). Whether participants show transient or sustained control modes may depend on the task at hand: Whereas Fischer et al. (2018) used a dual-task paradigm, the AX-CPT was used in Fröber and Dreisbach (2014, 2016a) as well as in Hefer and Dreisbach (2016; present thesis). The task-inherent efficiency of proactive control might be higher within the AX-CPT compared to a dual task (see results of Study 3 in which all participants shifted toward proactive cue usage). Thus, when reward is taken away, proactive cue usage might be kept at a high level when it is the most intrinsically rewarding strategy, but it might be given up when it is a highly effortful and less efficient strategy. Additionally, different results may have occurred because a dual task situation examines cognitive stability and flexibility in terms of task shielding and task relaxation, whereas the AX-CPT examines cognitive stability and flexibility in terms of increased and decreased cue maintenance.

Alternative explanations for reward-induced performance impairments

Impaired performance in the context of reward probably cannot be exclusively explained by reduced cognitive flexibility. Another well-known phenomenon and suitable factor to explain impaired performance in the context of reward is the so called "choking under pressure" phenomenon which describes situations in which increased motivation can undermine performance (Ariely, Gneezy, Loewenstein, & Mazar, 2009; Baumeister, 1984; Zedelius, Veling, & Aarts, 2011). Choking under pressure is not just poor performance but rather worse performance given one's skill level (Beilock & Carr, 2001; Beilock & Gray, 2012). There are two theories, distraction theories and explicit monitoring theories, that aim to explain the choking under pressure phenomenon. Distraction theories assume that pressure creates a distracting environment that impairs performance due to a shift of attention and working memory resources away from task execution. Thus, situation-related worries and task-irrelevant thoughts compete with attentional resources needed to perform the task. Consequently, a single-task situation turns into a dual-task situation. Explicit monitoring theories, instead, suggest that pressure raises self-consciousness and anxiety about performance which leads to a shift of too much attention toward skill processes thereby disrupting execution (Beilock & Carr, 2001;

DeCaro, Thomas, Albert, & Beilock, 2011). This latter theory may apply to the present results if choking under pressure did indeed have an effect: Participants might have shifted too much attention towards proactive cue usage disrupting the sensitivity to use (error) feedback from the environment for a change in response strategy. Another explanation for impaired performance is the level of arousal. According to the Yerkes-Dodson law, the relationship between arousal and effort (and consequently between effort and performance) looks like an inverted U-shape. Thus, performance is optimal at moderate levels of arousal, but declines when arousal is either too high or too low (Yerkes & Dodson, 1908). It may be that the arousal level of rewarded participants in the present research was too high, which might have led to high stress levels and resulted in too much effort. Finally, it is well known that intrinsic motivation can be decreased when contingent monetary payment is provided (for more information on the influence of extrinsic rewards on intrinsic motivation see Deci, Koestner, & Ryan, 1999; for a general overview see Sansone and Harackiewicz, 2007). This explanation, however, cannot be applied to the present finding because a reduction in intrinsic motivation should have resulted in task disengagement which in turn should have resulted in decreased cue usage and consequently better performance than observed. The present data are not suitable to decide to which degree “choking under pressure”, the level of arousal or other phenomena (cf. Braver et al., 2014) contributed to performance impairments in the context of reward, but they have presumably contributed to the impairment, in addition to the effect of reward-induced reductions in flexibility.

Reward does not equal reward

In order to not oversimplify the reward motivation-cognition interaction, some moderator variables – which have already been briefly mentioned in the introduction – will be discussed in this section. The present thesis focuses on the prospect of (conscious, unchanged high) performance-contingent reward on cognitive control; however, changing just one of these variables might result in completely different effects. For instance, recent research shows that the *immediate reward history* (whether reward incentives remain low, increase, remain high or decrease from one trial to the next) can also influence cognitive flexibility and stability. Using a task switching paradigm, Shen and Chun (2011) demonstrated that a sequential increase in reward from one trial to the next increases flexibility, as evidenced by smaller switch costs, whereas unchanged high reward promotes stability, as evidenced by higher switch costs and better performance on task repetitions. Fröber and Dreisbach (2016b) expanded on this research and showed that increases in reward magnitude also promote voluntary task switching. Thus, the prospect of reward can either promote cognitive stability or cognitive flexibility depending on the immediate reward history (see also Fröber, Raith, & Dreisbach, 2018; Fröber, Pfister, & Dreisbach, 2019). If reward incentives are given irrespective of performance (i.e., they are *performance non-contingent*), the pattern of results also completely changes. For instance, Fröber and Dreisbach (2014, 2016a) observed reduced proactive cue usage under performance non-contingent reward conditions. The influence of reward on cognitive control processes also depends on the timing of reward information. When reward information is provided prior to the task (i.e., *cue-based*), the result is a more proactive mode and preparatory strategies (cf. Studies 1 and 2 of the present thesis), whereas when reward is associated with certain stimuli or stimulus features that are part of the task itself (i.e., *stimulus-based*), the result is increased reactive processes (cf. Krebs, Boehler, & Woldorff, 2010; for more information see Krebs and Woldorff, 2017). A comparable distinction is the one between *reward prospect*, which activates the motivational component of reward, and *reward reception*, which activates the learning component of reward. Whereas reward reception might have reinforcing effects and enhance associative learning, reward prospect has motivational effects on cognition (for a recent review see Notebaert and Braem, 2015). Another critical factor in reward manipulation is whether reward is provided *consciously* or *unconsciously* to the recipient: Zedelius et al. (2014) summarized in their review that consciously and unconsciously perceived rewards can improve performance. Nevertheless, conscious (as compared to unconscious) rewards allow for a more strategic and efficient performance improvement. For instance, in the task preparation field, consciously-perceived rewards lead to strategic Speed-Accuracy Tradeoffs (SATs), whereas unconscious-perceived rewards only speed up responses (Bijleveld, Custers, & Aarts, 2010).

This brief overview of possible moderator variables of the reward effect underlines that the present finding of reward-induced increased cognitive stability at the cost of cognitive flexibility is restricted to manipulations of unchanged high, conscious, performance-contingent reward prospect in the AX-CPT. Moreover, in Studies 1 and 2, correct *and* fast performance was rewarded. It is highly plausible that the pattern of results changes when speed is no longer stressed.

The Vulnerability of the Positive Affect Effect

Study 3 pointed out that positive affect increases flexibility but that this affect-induced flexibility is vulnerable to experience with and time on a given task. Specifically, Study 3 showed that time on task is one moderator variable that counteracts the positive affect effect:

With increasing time on task, all participants shifted toward increased cue usage. This finding not only clarifies different findings by Chiew and Braver (2014) and Fröber and Dreisbach (2014), it could also explain why a recent study by Chaillou and colleagues (2018) also failed to replicate the positive affect effect on a behavioral level. The authors used a within-subjects design (comparable with Chiew and Braver, 2014) with a baseline and affect (50% positive and 50% neutral IAPS pictures preceding every trial) session at two different time points. Even though participants accomplished only 20 practice trials before the affect manipulation, which is comparable with Fröber and Dreisbach (2014), the authors failed to replicate the finding of decreased error rates on AY trials under positive affect. This failure to replicate might be caused by design differences: For example, in this study, participants had to respond to the cue *and* probe instead of to the probe only, and additionally there were extremely long sessions of 600 trials, which were divided into four blocks of 150 trials but were analyzed as a whole. Because Study 3 of the present thesis consisted of in total 420 trials (which were analyzed by block), it is plausible to assume that time on task effect similarly trumped the positive affect effect in Chaillou at al. (2018). A shift towards a more stable control mode with increasing time on task converges with the ideas put forth by Dreisbach and Fröber (2019), who argue that task context itself can also modulate the balance between stability and flexibility. The authors reviewed studies showing that a higher proportion of switch trials as compared to repeat trials reduces switch costs, which speaks to the idea of increased cognitive flexibility (cf., Dreisbach & Haider, 2006).

Further variables influencing the positive affect effect

In addition to time on task, there exist further variables that moderate the influence of positive affect on cognitive control and can therefore explain inconsistent findings (see also the General Discussion of Study 3). First, as already mentioned above, *performance-contingent reward* can trump the positive affect effect (Fröber & Dreisbach, 2014). Moreover, it is important to not lose sight of the fact that whether positive affect impairs or improves performance in a cognitive task (e.g., increased or decreased switch costs) depends on its *specific demands* (e.g., switching between naming color of ink and reading color words in a Stroop task in Phillips et al., 2002 vs. sorting card in a modified version of the Dimensional Change Card sorting task in Yang & Yang, 2014). The importance of task demands was already shown by Dreisbach and Goschke (2004) who investigated the different effects of positive affect on antagonistic cognitive control functions. The authors used a cognitive set-switching paradigm and participants had to respond to target stimuli in a pre-specified color (e.g., yellow) and to ignore distractors in a different color (e.g., green). In a perseveration condition, participants had to switch attention to targets in a novel color (e.g., blue) and ignore distractors in the previous target color (yellow). In a learned irrelevance or distractibility condition, participants had to instead switch attention to targets in the previously irrelevant color (green) and to ignore distractors in a new color (e.g., brown). The authors induced positive affect via positive or neutral pictures at the start of each trial. Dreisbach and Goschke (2004) showed that positive affect reduces switch cost in the perseveration condition but increases switch cost in the distractibility condition. Taken together, these findings show that positive affect reduces perseveration and facilitates flexible switching at the cost of increased distractibility. Thus, the positive affect effect comes along with performance costs and benefits.

These results were replicated by Liu and Wang (2014) who in addition showed that positive pictures *low in approach motivation* intensity increased flexibility at the cost of increased distractibility, whereas positive pictures *high in approach motivation* intensity increased perseveration and reduced distractibility (see also Liu and Xu, 2016, who observed decreased/increased proactive control under low-approach/high approach motivated positive affect). This work is consistent with research by Gable and Harmon-Jones (2008) who found a reduced global attentional focus in the context of high-approach-motivated positive affect, and increased global attentional focus in the context of low-approach-motivated positive affect (see also Domachowska et al., 2016). The effects of positive affective stimuli are not only moderated by the degree to which they evoke approach motivation, but also by the arousal level that they induce. Fröber and Dreisbach (2012) differentiated between *positive affect low vs. high in arousal* and found reduced reliance on informative cues in a simple response cueing paradigm but only under positive affect low in arousal.[24]

Taken together, positive affect is associated with costs and benefits depending on the processing demands of the task at hand. Moreover, the specific effect of positive affect further depends on moderator variables like approach and avoidance motivation and the level of arousal, and it can be trumped by reward motivation. Consequently, implications of the present results are restricted to the manipulation of mild positive affect low in arousal. It is also

[24] But see Cudo, Francuz, Augustynowicz, and Stróżak (2018) who used the AX-CPT and measured ERP components associated with proactive and reactive control. The authors presented positive pictures from the Nencki Affective Picture System with low or high level of arousal and approach motivation and found (in contrast to Fröber and Dreisbach, 2012) increased proactive control and reduced reactive control under low arousal. Several design differences may explain the inconsistent findings.

important to note that the finding of a decreasing positive affect effect with increasing time on task so far has only been shown for the AX-CPT as experimental paradigm.

Critical Comment on the AX-Continuous Performance Task

Even though the AX-CPT is a well-validated and frequently used paradigm to investigate the balance between proactive and reactive control, it also comes with some problems. First of all, proactive cue usage is a highly rewarding and efficient strategy within this paradigm. Braver et al. (2007) list several advantages of proactive control which are mostly fulfilled in the AX-CPT (i.e., highly informative cues) and therefore might explain why this is the preferred strategy in this paradigm (see also the General Discussion of Study 3). Thus, the effects of reward prospect on proactive cue usage could have been overestimated because of the task-inherent efficiency of proactive control. There is indeed evidence of proactive biases in healthy young adults (see Study 3 of the present thesis as well as Paxton et al., 2006). Moreover, a decline of the reward effect over time might go unnoticed because of a constantly high level of proactive control due to its task-inherent efficiency. Furthermore, the high efficiency of a proactive control strategy may suppress effects of positive affect (or at least reduce the effects as shown in Study 3).

Another issue with the AX-CPT concerns the lack of agreement about how to measure reactive control. Some authors argue that high interference on BX trials, as evidenced by high error rates and RTs on BX trials, indicates the use of reactive control (Chiew & Braver, 2014; Kray, Schmitt, Heintz, & Blay, 2015; Richmond, Redick, & Braver, 2015). Other studies calculate a proactive index from RTs and error rates on AY and BX trials as (AY-BX)/(AY+BX) to measure the relative tendency for proactive control (Braver et al., 2009; Chiew & Braver, 2014; Ličen, Hartmann, Repovš, & Slapničar, 2016). The closer the score is to +1, the higher the level of proactive control, and the closer the score is to -1, the higher the level of reactive control. This proactive index also assumes that high error rates on BX trials are an indicator of increased reactive control. This assumption is disputed by other authors who argue that a successful reliance on reactive control should result in high BX RTs along with *low* BX errors (cf. Braver et al., 2005; Chiew & Braver, 2017; Morales, Gómez-Ariza, & Bajo, 2013; Paxton et al., 2006). Gonthier et al. (2016b) argue that a selective enhancement of reactive control should lead to a shift from heightened BX errors to relatively slowed BX responding. It is becoming clear that the indicator for increased reactive control is not as clearly defined as for proactive control, which is consistently indexed by increased error rates on AY trials. Note also that there is one important reason why increased proactive control impairs AY performance on both error rates and RTs, but increased reactive control selectively impairs BX RTs: Whereas AY trials are context-independent trials because processing the cue is not necessary to respond correctly to the Y-probe, BX trials are instead context-dependent trials because cue processing *is* necessary on X-probes. In this context, it should also be mentioned that the measurement of reactive control on BX trials is inherently confounded by the degree to which proactive control is engaged, although we note that the modified version of the AX-CPT is more sensitive to reactive control. If one does not proactively prepare the nontarget response rule when the B-cue appears, increased error rates on BX trials might be the consequence of (1) reduced proactive cue usage, (2) poor reactive control to inhibit the X-probe/s triggered target response bias or (3) a mixture of both. With respect to this issue, Richmond and colleagues (2015) discuss whether a modification of the AX-CPT to encourage reactive control, actually enhance the reliance on reactive or rather discourage the reliance on proactive control.

Taken together, despite some drawbacks, the AX-CPT is a well-validated paradigm for investigating proactive cue usage. Nevertheless, it is highly important to extend the present results by using other paradigms, especially considering the finding of reward-induced increases in reactive control (Chaillou et al., 2017).

Limitations and Future Directions

There are some limitations of the present studies: First, the findings are restricted to manipulations of (conscious, extrinsic, unchanged high) performance-contingent reward prospect and mild positive affect induced by positive pictures (low in arousal) in the AX-CPT. In order to gain deeper understanding of the reward motivation–cognition and positive affect–cognition interaction, it is important to extend the present findings by further testing its boundary conditions using different experimental paradigms. Moreover, as in many other psychological studies, participants were mainly young, highly educated, female students, which is why one should be cautious about generalizing the results to a broader population, given the known relationship between proactive control and intelligence. A further common criticism is the lack of ecological validity. Thus, it is not clear to what extent the present results can be applied to everyday life. Nevertheless, despite some limitations, the results of the present thesis are very promising, add to an important research field and can serve as a starting point for future applied research: Given that reward plays a central role in our everyday life, there is a need for further research exploring more extensively the potentially negative consequences of reward prospect. Even though the effect of positive affect seems to be weaker than the effect of reward motivation, it is important to further investigate how our current affective state can influence cognitive performance. An important topic for future research will be the investigation of how the increasingly digital environment influences the balance between stability and flexibility. Cudo and colleagues (2019) demonstrated that a Facebook-related context shifts cognitive control toward a less proactive mode. They showed that Facebook-related primes reduced proactive control in the AX-CPT and provided first evidence that participants with higher scores on the Facebook intrusion scale showed signs of increased reactive control. Given the omnipresence of social media use, further investigations of its consequences for cognitive processes are warranted. Moreover, a recent correlational study found the first evidence that participants scoring higher on self-report measures of cognitive flexibility show stronger pro-environmental behavior (cf. Lange & Dewitte, 2019). While the underlying mechanisms still need to be understood, this shows that understanding how cognitive flexibility and stability is modulated is also of major interest for pressing issues in our society.

Conclusion

The findings presented here add to a growing literature that disentangles the influence of positive affect and reward motivation on cognitive control. Whereas positive affect and performance non-contingent reward reduce proactive cue usage (e.g., Fröber & Dreisbach, 2014; Study 3 of the present thesis), resulting in cognitive flexibility, performance-contingent reward has the opposite effect and increases proactive cue usage (e.g., Chiew & Braver, 2014; Fröber & Dreisbach, 2014; Studies 1 and 2 of the present thesis) resulting in enhanced cognitive stability. More precisely, Studies 1 and 2 clearly demonstrated the disadvantages of reward-induced increases in motivation: Reward prospect increases cognitive stability at the cost of decreased cognitive flexibility, as reflected by reduced sensitivity to feedback from the environment. Study 3 demonstrated the vulnerability of the positive affect effect to time on task effects. Thus, in our everyday life it is highly important to consider the consequences of higher cognitive stability vs. flexibility before choosing how to motivate ourselves and change our moods. Moreover, it is important to keep in mind that reward manipulations do not necessarily end up in performance improvements. Thus, whenever reward is used to guide attention and action, one should keep possible and unwanted consequences in mind.

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APPENDIX

Supplemental Material - Study 1

How Performance-Contingent Reward Prospect Modulates Cognitive Control: Increased Cue Maintenance at the Cost of Decreased Flexibility

by C. Hefer & G. Dreisbach, 2017, *Journal of Experimental Psychology: Learning, Memory, and Cognition*

http://dx.doi.org/10.1037/xlm0000397

Here we will present results for error rates and RTs from Experiment 1A, 1B and 1C in a more detailed way. We mainly focused on comparisons on AX and AY trials.

1. Experiment 1A

1.1 Error rate

Error rates were entered into a 3 (cue-probe condition: AX, AY, BX)[25] x 4 (block: baseline, block 1, 2 and 3) factors ANOVA (see Figure 2 in the ms). Analysis revealed a significant main effect of block, $F(3, 57) = 11.24$, $p < .001$, $\eta_p^2 = .37$. Error rates increased significantly from the baseline block to Block 1 ($F(1, 19) = 10.38$, $p < .01$, 5% vs. 14%), and from Block 2 to Block 3, $F(1, 19) = 12.66$, $p < .01$, 14% vs. 19%). The difference in error rates between Block 1 and Block 2 was nonsignificant ($p = .76$). There was also a main effect of cue-probe condition, $F(2, 38) = 41.34$, $p < .001$, $\eta_p^2 = .69$, with more errors in AY trials than in BX trials, $F(1, 19) = 36.1$, $p < .001$, 34% vs. 3%. The interaction of Cue-Probe Condition x Block also reached significance, $F(6, 114) = 24.38$, $p < .001$, $\eta_p^2 = .56$. Planned comparisons regarding AX and BX performance revealed no significant difference in the error rates of AX or BX trials from the baseline block to Block 1 or from Block 2 to Block 3 (all *F*s < 1.53, all *p*s > .23). From Block

[25] BY trials had to be excluded because participants made no errors on BY trials in Block 3.

1 to Block 2 a small but significant decrease of error rates on AX trials ($F(1, 19) = 8.1$, $p = .01$, 2.1% vs. 1.3%) and a small but only marginally significant increase of error rates on BX trials ($p = .054$, .63% vs. 2.5%) was found.

The significant decrease of AX errors and increase of BX errors from Block 1 to Block 2 could be interpreted as a sign of decreased cue maintenance. However, this should be interpreted with caution because the differences in AX and BX errors are very small (AX: 2.1% vs. 1.3%, BX: 0.63% vs. 2.5%).

1.2 RT data[26]

RTs were entered into a 4 (cue-probe condition: AX, AY, BX, BY) x 4 (block: baseline, block 1, 2 and 3) factors design (see Figure 2 in the ms). Analysis yielded a significant main effect of block, $F(3, 48) = 57.85$, $p < .001$, $\eta_p^2 = .78$, reflecting significantly faster RTs in Block 1 than in the baseline block, $F(1, 16) = 63.6$, $p < .001$, 425 ms. vs. 299 ms, significantly faster RTs in Block 1 than in Block 2, $F(1, 16) = 7.6$, $p = .01$, 299 ms. vs. 324 ms, and significantly faster RTs in Block 3 than in Block 2, $F(1, 16) = 25.7$, $p < .001$, 264 ms vs. 324 ms. There was also a main effect of cue-probe condition, $F(3, 48) = 200.13$, $p < .001$, $\eta_p^2 = .93$, with participants responding slower on AY trials than on B-cue trials (both *F*s > 335.8, both *p*s < .001). There was no difference in RTs on BX and BY trials ($p = .2$). These main effects were qualified by a significant interaction of Block x Cue-Probe Condition, $F(9, 144) = 8.89$, $p < .001$, $\eta_p^2 = .36$.

2 Experiment 1B

2.1 Error rate

Error rates were entered into a 2 (group: reward, neutral) x 4 (block: 2 x AX-70 vs. 2 x AX-40) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 3 in the ms). There was a significant main effect of group, $F(1, 38) = 15.15$, $p < .001$, $\eta_p^2 = .29$. Overall, the reward group committed significantly more errors than the neutral group (10% vs. 3%). There was also a main effect of cue-probe condition, $F(3, 114) = 62.79$, $p < .001$, $\eta_p^2 = .62$. Participants made more errors on AY-trials than on BX-trials ($F(1, 38) = 58.9$, $p < .001$, 19% vs. 2.5%). BX errors were higher than BY errors, $F(1, 38) = 6.6$, $p < .01$, 2.5% vs. 0.9%. The significant main effect of block, $F(3, 114) = 25.39$, $p < .001$, $\eta_p^2 = .4$, reflected higher error rates in Block

[26] Only 17of 20 participants were included in the RT analysis because three participants had an error rate of 100% on AY trials (one participant in Block 2 and 3, two participants in Block 3 only) (cf. Fröber & Dreisbach, 2014).

1.2 than in Block 2.1 ($F(1, 38) = 40.57$, $p < .001$, 9.4% vs. 4.1%). The interaction Group x Block reached significance, $F(3, 114) = 9.96$, $p < .001$, $\eta_p^2 = .21$, as well as the interaction Group x Cue-probe condition, $F(3, 114) = 23.67$, $p < .001$, $\eta_p^2 = .38$, and Block x Cue-probe condition, $F(9, 342) = 33.8$, $p < .001$, $\eta_p^2 = .47$. Critically, the three-way interaction of Group x Block x Cue-probe condition was also significant, $F(9, 342) = 12.83$, $p < .001$, $\eta_p^2 = .25$.

2.2 RT data[27]

Mean median RTs were entered into a 2 (group: reward, neutral) x 4 (block: 2 x AX-70 vs. 2 x AX-40) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 4 in the ms). The analysis revealed a significant main effect of group, $F(1, 36) = 17.91$, $p < .001$, $\eta_p^2 = .03$, reflecting lower RTs in the reward group (283 ms) than in the neutral group (374 ms). There was also a main effect of cue-probe condition, $F(3, 108) = 356.26$, $p < .001$, $\eta_p^2 = .91$. Participants answered slower on AY trials than on AX and B-cue trials (all *F*s > 287.62, all *p*s < .001). The main effect of block was far from significance ($F(3, 108) = 1.4$, $p = .24$). The interaction Block x Group was significant, $F(3, 108) = 7.57$, $p < .001$, $\eta_p^2 = .17$, as well as the interaction of Block x Cue-probe condition, $F(9, 324) = 11.38$, $p < .001$, $\eta_p^2 = .24$. Planned comparisons on the Block x Group interaction showed significantly faster RTs in Block 1.2 than in Block 1.1 in the neutral group ($F(1, 36) = 8.17$, $p < .01$, 395 ms vs. 372 ms). There was no further significant decrease or increase in RTs from Block 1.2 to Block 2.1 and to Block 2.2 (*F*s < 3.9, *p*s > .06). The reward group showed a significant increase in RTs from Block 1.2 to Block 2.1 ($F(1, 36) = 5.5$, $p < .05$, 273 ms vs. 293 ms). The reward group responded significantly faster in all blocks as compared to the neutral group (*F*s > 7.68, *p*s < .01). Planned comparisons on the interaction between Block x Cue-Probe Condition showed a significant increase of RTs in AX trials from Block 1.2 to Block 2.1 ($F(1, 36) = 166.12$, $p < .001$, 335 ms vs. 404 ms) as well as a significant decrease of RTs in AY trials from Block 1.2 to Block 2.1 ($F(1, 36) = 5.9$, $p < .02$, 518 ms vs. 491 ms) suggesting an adaptation to changed task conditions in Block 2.1: a reduction in cue usage hampers a fast response in AX trials (increase in AX RTs) but facilitates the correct response in AY trials (decrease in AY RTs). The interaction Group x Cue-probe condition and the three-way interaction did not prove reliable ($F < 1.25$, $p > .3$).

[27] Only 18 participants were included into the RT analyses because two participants had an AY error rate of 100% in Block 1.1 or Block 1.2.

3 Experiment 1C

3.1 Error rate

Error rates were entered into a 3 (group: neutral, Rew-Neut, Rew-Rew) x 4 (block: 2 x AX-70 vs. 2 x AX-40) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 5 in the ms). The factor group reached significance, $F(2, 89) = 7.42$, $p < .001$, $\eta^2_p = .14$, with the lowest error rate in the neutral group (10%) followed by the Rew-Neut group (15.8%) and the Rew-Rew group (19%). There was also a significant main effect of block, $F(3, 267) = 17.6$, $p < .001$, $\eta^2_p = .17$, reflecting a higher error rate in Block 1.2 than in Block 2.1 ($F(1, 89) = 13.1$, $p < .001$, 16% vs. 13%). A significant main effect of cue-probe condition was observed, $F(3, 267) = 88.68$, $p < .001$, $\eta^2_p = .5$. Participants made more errors on AY trials (24%) than on BX trials (17%) ($F(1, 89) = 30.7$, $p < .001$), than on BY trials (13%) ($F(1, 89) = 115.6$, $p < .001$). Error rates on BX trials were higher than on BY trials ($F(1, 89) = 13.51$, $p < .001$). The interaction Group x Cue-probe condition, $F(6, 267) = 5.62$, $p < .001$, $\eta^2_p = .11$, Block x Cue-probe condition, $F(9, 801) = 7.3$, $p < .001$, $\eta^2_p = .08$, as well as the three-way interaction, $F(18, 801) = 2.27$, $p < .01$, $\eta^2_p = .05$, were significant. Only the Block x Group interaction failed to reach significance ($p = .06$).

BX and BY trials[28]. From Hefer and Dreisbach (2016) we know that performance-contingent reward impairs the overall accuracy particularly due to higher error rates on AY *and* BY errors in the modified version of the AX-CPT. We will therefore also compare BX and BY trial performance between the groups.

In none of the four blocks, there was a performance difference on BX trials between the Rew-Neut and neutral group (all *F*s < 1.4, all *p*s > .25). The Rew-Rew group made significantly more errors on BX trials than the neutral group in Block 1.1 only ($F(1, 89) = 7.68$, $p < .05$, 27% vs. 14%). Only in Block 2.1, the Rew-Neut group made significantly more errors on BY trials than did the neutral group ($F(1, 89) = 5.32$, $p < .05$, 13% vs. 6%). The Rew-Rew group made significantly more errors on BY trials than did the neutral group in Block 1.2 and Block 2.1 (both *F*s > 4.4, both *p*s < .04). There was no performance difference on BY trials between the groups in Block 1.1 and Block 2.2 (both *F*s < 3.5, both *p*s > .07).

Increased error rates on BY trials in the Rew-Rew group as compared to the neutral group are a phenomenon already known from a previous study from our laboratory (Hefer & Dreisbach, 2016). There we argued that the repeated erroneous application of the target rule to

[28] We argue that both BX and BY trials are sensitive for increased cue maintenance because the B-cue is valid for 100% and indicates that – irrespective of the following probe – the nontarget response will be required.

the Y-probe on AY trials might have created an association between the Y-probe and the (erroneously applied) target rule which then also got retrieved in some instances when the Y-probe was preceded by a B-cue. Such an effect is not observed in the standard AX-CPT (even though the higher frequency of AY-errors might also create an association between the Y-probe and the wrong target-response) because in the standard AX-CPT the B-cue already allows response preparation thereby preventing the retrieval of the wrong target-response with the onset of the Y-probe.

3.2 RT data

RTs were entered into a 3 (group: neutral, Rew-Neut, Rew-Rew) x 4 (block: 2 x AX-70 vs. 2 x AX-40) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA (see Figure 6 in the ms). The main effect of group reached significance, $F(2, 89) = 23.13$, $p < .001$, $\eta_p^2 = .34$, with the lowest RTs in the Rew-Rew group (532 ms) followed by the Rew-Neut group (630 ms) and the neutral group (786 ms). There was also a main effect of block, $F(3, 267) = 2.87$, $p = .04$, $\eta_p^2 = .03$, reflecting faster RTs in Block 1.2 (635 ms) than in Block 2.1 (663 ms), $F(1, 89) = 9.35$, $p < .01$. A main effect of cue-probe condition was also found ($F(3, 267) = 163.7$, $p < .001$, $\eta_p^2 = .65$): RTs on AY trials (819 ms) were slower than on B-cue trials (both *F*s > 125.88, both *p*s < .001). RTs on BX and BY trials did not differ significantly ($p = .17$, 645 ms vs. 633 ms). The interaction Group x Cue-probe condition, $F(6, 267) = 5.4$, $p < .001$, $\eta_p^2 = .11$, Block x Cue-probe condition, $F(9, 801) = 10.54$, $p < .001$, $\eta_p^2 = .11$, Group x Block, $F(6, 267) = 12.5$, $p < .001$, $\eta_p^2 = .22$, as well as the three-way interaction, $F(18, 801) = 2.25$, $p < .01$, $\eta_p^2 = .05$, reached significance. Overall cue-probe conditions, faster RTs for both reward groups as compared to the neutral group were observed in Block 1.1, Block 1.2 and Block 2.1 (all *F*s > 10.27, all *p*s < .01) suggesting a strong cue usage. In Block 2.2, there was only a significant RT difference between the Rew-Rew and neutral group, $F(1, 89) = 35.3$, $p < .001$, 508 ms vs. 759 ms, but no longer between the Rew-Neut and neutral group, $p = .13$, 695 ms vs. 759 ms.

4 Speed accuracy tradeoff

What speaks against the concern of a SAT is that reward incentives resulted in generally faster RTs as compared to the neutral group (Experiment 1B and 1C) / baseline block (Experiment 1A) whereas error rates were *particularly* higher on AY trials. In Experiment 1A, there was an increase in error rates on AY trials only indicating a real shift towards increased cue maintenance. But, in Experiment 1B the reward group made not only more errors on AY trials but also on AX trials as compared to the neutral group in Block 1.1 (first AX-70 block) ($F(1, 38) = 4.1$, $p < .05$). Therefore, an interaction contrast Group (neutral, reward) x Cue-Probe-condition (AX, AY) in Block 1.1 was conducted. The performance difference between the reward group and the neutral group was significantly higher on AY trials (30%) as compared to AX trials (1%) suggesting increased error rates particularly in AY trials ($F(1, 38) = 15.68$, $p < .001$). There was no difference between the neutral and reward group in B-cue errors in the rewarded Block 1.1 or Block 1.2 (all *F*s < 2.1, all *p*s > .16). In Experiment 1C, the Rew-Neut group made more errors on AX trials in Block 1.1 ($F(1, 89) = 4.86$, $p < .05$, 7% vs. 3%) and Block 1.2 ($F(1, 89) = 4.68$, $p < .05$, 6% vs. 3%) as compared to the neutral group. Again, interaction contrasts Group (Rew-Neut, neutral) x Cue-Probe Condition (AX, AY) in Block 1.1 and Block 1.2 were conducted. For both blocks, the performance difference on AY trials was significantly higher than for AX trials ($F(1, 89) = 17.91$, $p < .001$, 25% vs. 4%, $F(1, 89) = 7.5$, $p < .01$, 15% vs. 3%) suggesting a real shift towards increased cue maintenance rather than a SAT.

Higher error rates on AX trials in the reward group as compared to the neutral group may be explained by the fact that the A-cue is not 100% valid. That is, error rates increased especially in less predictive trial types (A-cue trials) - but more so on AY trials.

The Rew-Rew group made more errors on BX trials only in Block 1.1 as compared to the neutral group ($F(1, 89) = 7.68$, $p < .01$, 27% vs. 14%). Again, an interaction contrast Group (Rew-Rew, neutral) x Cue-Probe Condition (AY, BX) for error rates in Block 1.1 was conducted. The interaction contrast failed to reach significance indicating a comparable performance difference between groups on AY and BX trials ($F(1, 89) = 3.1$, $p = .08$, 24% vs. 13%). As the Rew-Rew group made more errors only in Block 1.1 on BX trials as compared to the neutral group, these errors might be driven by the unexpected chance to earn money on this task. There was no further performance difference on BX trials between the Rew-Rew group and neutral group in Block 1.2, Block 2.1 or Block 2.2 (all *F*s < 2.3, all *p*s > .14). The Rew-Rew group made also significantly more errors on BY trials in Block 1.2 ($F(1, 89) = 4.4$, $p < .05$, 18% vs. 9%) and Block 2.1 ($F(1, 89) = 5.93$, $p < .05$, 14% vs. 6%) as compared to the neutral group. There was no further performance difference on BY trials between the groups in Block 1.1 and Block 2.2 (2 (both *F*s < 3.5, both *p*s > .06). Interaction contrasts Group (Rew-Rew, neutral) x Cue-Probe Condition (AY, BY) for error rates in Block 1.2 and Block 2.1 were conducted. The interaction contrast was nonsignificant, $F(1, 89) = 1.54$, $p = .22$, for Block 1.2 suggesting comparable error rate differences between the groups on AY (16%) and BY trials (9%). For Block 2.1 the interaction contrast was significant, $F(1, 89) = 9.2$, $p < .01$, due to higher an error rate difference between the groups on AY trials (18%) than on BY trials (8%). Only in the last Block 2.2, the Rew-Rew group showed higher error rates on AX trials than the neutral group, $F(1, 89) = 6.57$, $p < .01$. The corresponding interaction contrast Group (Rew-Rew, neutral) x Cue-Probe Condition (AX, AY) for error rates in Block 2.2 reached significance, $F(1, 89) = 10.83$, $p < .01$, indicating higher error difference between the groups on AY trials (15%) than on AX trials (5%). In Block 1.1/2 and Block 2.1 the Rew-Rew did not make significantly more errors on AX trials than did the neutral group, $F < 3.9$, $p > .05$. This confirms once again a real shift towards increased cue maintenance rather than a pure speed strategy as evidenced by *particularly* higher error rates on AY trials in the Rew-Rew group as compared to the neutral group.

Taken together, the reward groups (especially the Rew-Rew group) showed increased error rates not only on AY but also in some blocks on AX, BX and BY trials. Despite this finding, we argue that our results are driven by the motivational effect of reward rather than a speed-accuracy trade-off because in most of the cases the error rates were increased especially on AY trials. We argue that comparable error rate differences between the Rew-Rew and neutral group on AY and BX/BY trials in Block 1.1 / Block 1.2 rather support our assumption of a shift towards increased cue maintenance than contradict it: The repeated erroneous application of the target rule to the Y-probe on AY trials might have created an association between the Y-probe and the (erroneously applied) target rule which then also got retrieved in some instances when the Y-probe was preceded by a B-cue (cf. Hefer & Dreisbach, 2016). The repeated correct application of the target rule to the X-probe on AX trials might have created an association between the X-probe and the target rule which then also got retrieved in some instances when the X-probe was preceded by a B-cue. In other words, increased BX / BY errors may be direct consequences of increased A-cue maintenance.

Supplemental Material - Study 2

Supplemental Materials

Prospect of performance-contingent reward distorts the action-relevance of predictive context information

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Experiment 2A

*Error Rates – Block 1.1/2 (*AX40-AY40*)*

Error rates were entered into a 3 (group: reward, neutral-reward, neutral) x 2 (block: Block 1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA. There was a significant main effect of group, $F(2, 104) = 14.8$, $p < .001$, $\eta_p^2 = .22$. The reward group committed more errors than the neutral group which in turn committed more errors than the neutral-reward group. There was also a significant main effect of cue-probe condition, $F(3, 312) = 9.32$, $p < .001$, $\eta_p^2 = .08$. Participants made more errors on AY trials relative to AX trials, $t(106) = 5.41$, $p < .001$, $d = 0.54$, and relative to BY trials, $t(106) = 2.14$, $p = .03$, $d = 0.19$. Error rates on AY and BX trials, $t(106) = 1.03$, $p = .31$, $d = 0.09$, as well as error rates on BX and BY trials, $t(106) = 0.97$, $p = .33$, $d = 0.1$, did not differ significantly. The main effect of block was also significant, $F(1, 104) = 6.74$, $p = .01$, $\eta_p^2 = .06$, with higher error rates in Block 1.1 as compared to Block 1.2.

The interaction between group and cue-probe condition, $F(6, 312) = 3.36$, $p = .003$, $\eta_p^2 = .06$, was significant (please see the ms). The interaction between group and block, $F(2, 104) = 1.03$, $p = .36$, $\eta_p^2 = .02$, and between block and cue-probe condition, $F(3, 312) = 0.65$, $p = .58$, $\eta_p^2 = .01$, did not reach significance. The three-way interaction was also not significant, $F(6, 312) = 1.81$, $p = .1$, $\eta_p^2 = .03$.

*Error Rates – Transition from Block 1.2 (*AX40-AY40*) to Block 2.1/2 (AX70-AY10)*

Results can be found in the ms.

Experiment 2B

*Error Rates – Block 1.1/2 (*AX40-AY40*)*

Error rates were entered into a 2 (group: reward, neutral) x 2 (block: Block 1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA. There was a significant main effect of group, *F*(1, 61) = 13.58, *p* < .001, η_p^2 = .18, with higher error rates in the reward group than in the neutral group. There was also a main effect of cue-probe condition, *F*(3, 183) = 2.9, *p* = .04, η_p^2 = .05. Participants committed more errors on AY trials than on BY trials, *t*(62) = 2.66, *p* = .01, *d* = 0.3. Error rates on AY trials and AX trials, *t*(62) = 1.45, *p* = .15, *d* = 0.19, and on AY trials and BX trials, *t*(62) = 0.15, *p* = .88, *d* = 0.02, did not differ significantly. Error rates on BX trials were significantly higher than on BY trials, *t*(62) = 2.78, *p* = .01, *d* = 0.27. The main effect of block was not significant, *F*(1, 61) = 2.56, *p* = .11, η_p^2 = .04.

The interaction between group and cue-probe condition approached significance, *F*(3, 183) = 2.58, *p* = .055, η_p^2 = .04 (please see the manuscript). All further interactions did not reach significance (Block x Cue-probe condition: *F*(3, 183) = 0.2, *p* = .9, η_p^2 = .003, Group x Block: *F*(1, 61) = 0.16, *p* = .69, η_p^2 = .003, Group x Block x Cue-probe condition: *F*(3, 183) = 0.21, *p* = .89, η_p^2 = .003).

*Error Rates – Transition from Block 1.2 (*AX40-AY40*) to Block 2.1/2 (AX70-AY10)*

Results can be found in the ms.

Experiment 2C

*Error Rates – Block 1.1/2 (*AX40-AY40*)*

Error rates were entered into a 2 (group: reward, neutral) x 2 (block: Block 1.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA. The main effect of group was not significant, *F*(1, 64) = 3.07, *p* = .08, η_p^2 = .05. The main effect of block, *F*(1, 64) = 5.12, *p* = .03, η_p^2 = .07, reached significance reflecting higher error rates in the first AX40-AY40 block as compared to the second AX40-AY40 block. The main effect of cue-probe condition, *F*(3, 192) = 7.86, *p* < .001, η_p^2 = .11, was significant. Error rates on AY and AX trials, *t*(65) = 0.89, *p* = .38, *d* = 0.11, and on AY and BX trials, *t*(65) = 1.64, *p* = .11, *d* = 0.24, did not differ significantly. Participants committed more errors on AY than on BY trials, *t*(65) = 4.47, *p* < .001, *d* = 0.54, and more errors on BX than on BY trials, *t*(65) = 2.31, *p* = .02, *d* = 0.26. Error rates on AX trials were higher than on B-cue trials, both *t*s > 2.34, both *p*s < .02, both *d*s > 0.34.

No interaction reached significance (Block x Group: $F(1, 64) = 1.17$, $p = .28$, $\eta_p^2 = .02$, Group x Cue-probe condition: $F(3, 192) = 1.23$, $p = .3$, $\eta_p^2 = .02$, Block x Cue-probe condition: $F(3, 192) = 0.34$, $p = .8$, $\eta_p^2 = .01$, Block x Group x Cue-probe condition: $F(3, 192) = 0.18$, $p = .91$, $\eta_p^2 = .003$).

Error Rates – Transition from Block 1.2 (AX40-AY40) to Block 2.1/2 (AX70-AY10)

Error rates were entered into a 2 (group: reward, neutral) x 3 (block: Block 1.2, Block 2.1/2) x 4 (cue-probe condition: AX, AY, BX, BY) mixed factors ANOVA. The three-way interaction just reached significance, $F(6, 384) = 2.12$, $p = .0501$, $\eta_p^2 = .03$. Within-group comparisons showed no significant increase / decrease in B-cue trials from Block 1.2 to Block 2.1 in the reward group, both *t*s < 1.65, both *p*s > .11, both *d*s < 0.24. The neutral group showed a significant increase only in BX errors from Block 1.2 to Block 2.1, $t(31) = 2.07$, $p = .05$, $d = 0.32$. There was no further significant increase / decrease in error rates on B-cue trials from Block 2.1 to Block 2.2 in the neutral group, both *t*s < 1.87, both *p*s > .07, both *d*s < 0.26. The reward group showed a significant only on BY errors from Block 2.1 to Block 2.2, $t(33) = 2.07$, $p = .05$, $d = 0.34$.