Emotion versus Motivation: Probing Dissociable Effects on Cognitive Control Through Task Performance, Pupillometry Methods, and Individual Differences

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Emotion versus Motivation: Probing Dissociable Influences on Cognitive Control Through Task Performance, Pupillometry Methods, and Individual Differences

by

Kimberly Sarah Chiew

A dissertation presented to the Graduate School of Arts and Sciences of Washington University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

December 2013

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# Table of Contents

List of Figures ............................................................................................................................... vi

List of Tables ................................................................................................................................. vii

Acknowledgments ......................................................................................................................... ix

Abstract ......................................................................................................................................... xi

Introduction ..................................................................................................................................... 1

   Emotion and Motivation: Terminology and Conceptualization ............................................... 3

   Neural and Psychological Mechanisms of Positive Emotion ................................................... 5

   Neural and Psychological Mechanisms of Reward Motivation .............................................. 7

Examining Emotional and Motivational Effects on Cognitive Control Dynamics .......... 10

Using Pupillometry to Examine the Temporal Dynamics of Cognitive Control ............... 14

Individual Difference Measures and Cognitive Control .............................................................. 17

Comparing Emotional and Motivational Influences on Cognitive Control: Approach
   of the Current Study .................................................................................................................... 18

Methods ......................................................................................................................................... 22

   Participants ................................................................................................................................. 22

   General Study Structure .......................................................................................................... 23

   SAM Assessments ..................................................................................................................... 27

   AX-CPT Paradigm ..................................................................................................................... 27

Passive Viewing Run (in Emotion Session) ............................................................................. 30

Fixation Run with Pupillometry ................................................................................................. 32

Apparatus ...................................................................................................................................... 32

Pupillometry Data Collection ...................................................................................................... 32
Data Analysis: Task Performance ................................................................. 33
Data Analysis: Pupillometric Measures ...................................................... 35
Individual Difference Measures ................................................................. 36
Results ........................................................................................................... 38
Effects of Emotion Inductions: SAM Assessments ....................................... 38
Effects of Emotion Inductions: IAPS Passive Viewing Run .......................... 42
Results: Task Performance ........................................................................... 46
Reward AX-CPT ......................................................................................... 46
   Global Incentive Effects ........................................................................ 46
   Block-Based Effects ............................................................................. 47
   Trial-Based Effects ............................................................................. 48
Emotion AX-CPT ....................................................................................... 50
   Block-Based Effects ............................................................................. 50
   Trial-Based Effects ............................................................................. 51
Emotion versus Reward AX-CPT ................................................................. 52
   Block-Based Effects ............................................................................. 52
   Trial-Based Effects ............................................................................. 55
Results: Pupillometry Measures During AX-CPT Performance ..................... 57
Reward AX-CPT ......................................................................................... 57
   Block-Based Effects ............................................................................. 57
   Trial-Based Effects ............................................................................. 58
Emotion AX-CPT ....................................................................................... 60
   Block-Based Effects ............................................................................. 60
Trial-Based Effects ................................................................. 61

Emotion versus Reward AX-CPT .................................................. 62

Block-Based Effects ................................................................. 62

Trial-Based Effects ................................................................. 63

Transient Pupil Effects as a Function of Session and Block Context 65

Time on Task Effects: Task Performance and Pupil Activity ...................... 68

Pupil-Behaviour Correlations .......................................................... 75

Results: Individual Difference Measures ........................................... 79

Hypothesis 1 Analyses: Reward Sensitivity and Proactive Control .......... 81

Reward Sensitivity and Proactive Control: Developing a Reward Sensitivity Measure via Factor Analysis .................................................. 85

Hypothesis 2 Analyses: Positive Emotion Induction, Positive Affect/Reward-Related Individual Differences, and Changes in Control in the Positive Emotion Task Block ................................................................. 92

Task Performance and Pupil Activity in Top Thirty Reward Sensitive Individuals ................................................................. 94

Hypothesis 3 Analyses: Working Memory Capacity, Cognitive Control, & Pupil Activity ........................................................................... 100

Hypothesis 4 Analyses: Trait Anxiety, Cognitive Control, and Pupil Dilation ........................................................................... 104

Discussion ....................................................................................... 105

Aim 1: Effects of Reward Incentive and Positive Emotion Manipulations on Performance and Pupil Activity .................................................. 106
List of Figures

Figure 1 ................................................................................................................................. 25
Figure 2 ................................................................................................................................. 29
Figure 3 ................................................................................................................................. 38
Figure 4 ................................................................................................................................. 45
Figure 5 ................................................................................................................................. 48
Figure 6 ................................................................................................................................. 51
Figure 7 ................................................................................................................................. 53
Figure 8 ................................................................................................................................. 54
Figure 9 ................................................................................................................................. 55
Figure 10 ................................................................................................................................. 56
Figure 11 ................................................................................................................................. 58
Figure 12 ................................................................................................................................. 59
Figure 13 ................................................................................................................................. 61
Figure 14 ................................................................................................................................. 62
Figure 15 ................................................................................................................................. 63
Figure 16 ................................................................................................................................. 64
Figure 17 ................................................................................................................................. 66
Figure 18 ................................................................................................................................. 69
Figure 19 ................................................................................................................................. 70
Figure 20 ................................................................................................................................. 70
Figure 21 .................................................................................................................................. 78
Figure 22 .................................................................................................................................. 94
List of Tables

Table 1 ..........................................................................................................................31
Table 2 .......................................................................................................................... 81
Table 3 .......................................................................................................................... 82
Table 4 .......................................................................................................................... 85
Table 5 .......................................................................................................................... 87
Table 6 .......................................................................................................................... 88
Table 7 .......................................................................................................................... 90
Table 8 .......................................................................................................................... 91
Table 9 .......................................................................................................................... 96
Table 10 ......................................................................................................................... 97
Table 11 ......................................................................................................................... 98
Table 12 ......................................................................................................................... 99
Table 13 ......................................................................................................................... 103
Table S1 ......................................................................................................................... 147
Table S2 ......................................................................................................................... 153
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ABSTRACT OF THE DISSERTATION

Emotion versus Motivation: Probing Dissociable Influences on Cognitive Control Through Task Performance, Pupillometry Methods, and Individual Differences

by

Kimberly Sarah Chiew

Doctor of Philosophy in Psychology

Washington University in St. Louis, 2013

Professor Todd S. Braver, Chair

It is becoming increasingly appreciated that affective influences can contribute strongly to goal-oriented cognition and behaviour. However, much work is still needed to properly characterize these influences and the mechanisms by which they contribute to cognitive processing. An important question concerns the nature of emotional manipulations (i.e., direct induction of affectively valenced subjective experience) versus motivational manipulations (e.g., delivery of performance-contingent rewards and punishments) and their impact on cognitive control. Given previous empirical evidence suggesting that positive emotion may enhance cognitive flexibility and reactive control, while performance-contingent rewards may enhance goal maintenance and proactive control, we sought to directly compare the effects of positive emotion and reward manipulations on cognitive control in a single group of subjects, using the AX-Continuous Performance Task (AX-CPT) paradigm, which allows measurement of the relative balance between proactive and reactive cognitive control. Pupil dilation during task performance was measured using high-resolution pupillometry as a secondary, high temporal-resolution
measure of cognitive dynamics, and individual difference measures (both personality and cognition-related) were collected to examine whether the effects of emotional and motivational manipulations on cognition were mediated by such measures. We observed expected increases in proactive control and pupil dilation under reward incentive, at both sustained (block-based) and transient (trial-based) timescales. Effects under positive emotion were more complex: while performance and pupil activity were also suggestive of a mild shift towards proactive control, this effect was much weaker than under reward incentive. Surprisingly, reward-related individual differences did not predict changes in cognitive performance or pupil dilation under incentive. These findings provide evidence that positive emotion and reward may be dissociable constructs. Further, they replicate previous findings that reward may enhance goal representation and proactive control, but attest to the complexity and heterogeneity of possible positive emotion effects.

Experimental limitations and future directions are discussed as possible strategies to address these findings and extend their observations, towards the goal of building a more comprehensive science of affect-cognition interactions.
Introduction

Human nature is uniquely characterized by the flexibility, complexity, and sophistication with which thought and behaviour can be deployed in the service of a goal. This ability is thought to depend on cognitive control, a collection of mechanisms by which the human cognitive system adaptively configures itself to optimally perform specific tasks (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Braver, Barch, & Cohen, 2002; J. D. Cohen, Braver, & O'Reilly, 1996; Miller & Cohen, 2001). Most of the goals pursued in daily life are emotionally or motivationally meaningful – i.e., we pursue goals to obtain outcomes that are pleasurable or important to survival, and avoid outcomes that are not. It has long been understood that such affective significance is central to determining the goals around which human behaviour is organized: indeed, impairments in affectively driven goal pursuit may be a critical component of a number of psychiatric disorders, such as depression and schizophrenia (Dowd & Barch, 2010; Pessoa, 2008).

Emotional and motivational effects are major influences in determining and prioritizing the goals that direct controlled behaviour, but only recently have such affective influences been examined in the context of the cognitive mechanisms by which such behaviour is governed. Much of the experimental research examining such influences on cognitive control has involved one of two types of manipulations: emotional manipulations, in which valenced subjective experience is directly induced (e.g., through mood inductions or exposure to emotional stimuli) or motivational manipulations, where motivational state is altered through the introduction of rewarding or punishing incentives. Both types of manipulations are thought to be affectively significant and impact goal pursuit and cognitive control. However, for the most part, experimental studies examining the effects of
these manipulations have focused on one type or another; thus, these lines of research have been carried out largely in separation. Theoretical and experimental literature suggests that emotion and motivation are highly interrelated but distinct concepts (Carver, 2003; P. J. Lang & Bradley, 2008; Roseman, 2008) that may be dissociable (e.g., “liking” versus “wanting” behaviours have been neurally dissociated in rodents (Berridge, 1996) but the extent to which their influences on human cognition may be considered dissociable remains an open question. Exploring this question is the primary goal of the present study. To facilitate comparison between emotional and motivational influences on cognition, we chose to restrict our focus to positive emotion and reward incentives. It is, of course, also crucial to explore the relationship between negative emotions and punishment/avoidance-based motivational states, but as positive and negative emotion may be independent of one another (Watson, Clark, & Tellegen, 1988), investigating relations between negative emotion and punishment/avoidance are beyond the scope of the present investigation.

We used task performance measures and high-resolution pupillometry to measure the temporal dynamics of cognitive control and its modulation by positive emotion manipulations compared to reward incentive manipulations. We also utilized a large sample size and collected individual difference measures, both personality and cognition-related, to examine how these individual differences might mediate relationships between emotion/reward manipulations and related changes in cognitive control dynamics. In this introduction, we will briefly review how emotion and motivation as constructs have been conceptualized, their underlying biological mechanisms, evidence of their effects on cognitive control, and the use of pupillometry as a potential tool for examining such effects. This review is adapted from our recently published paper that explores this literature more.
deeply (Chiew & Braver, 2011). Following this review, we outline how the present study aims to clarify the relationship between these constructs and their influences on cognition through direct empirical comparison.

*Emotion and Motivation: Terminology and Conceptualization*

Emotion and motivation are highly related constructs within the domain of affect (P. J. Lang & Bradley, 2008; Rolls, 2000), but their influences on cognition generally have not been explicitly considered in relation to one another. When trying to investigate the impact of each on cognitive performance, it is important to provide working definitions of relevant terms, so as to begin carefully examining how these constructs may relate to one another.

One review suggests that emotions are best functionally defined as “psychological or physiological states that index occurrences of value” (Dolan, 2002). As this description suggests, emotion is generally conceptualized as a construct that can be decomposed into multiple subcomponents defining the relation between individual and environment. Davidson and colleagues (Davidson, Ekman, Saron, Senulis, & Friesen, 1990) suggest that emotions are comprised of three elements: autonomic reactions, cognitions, and behaviours. More recently, Roseman (Roseman, 2008) asserts that emotion can be thought of as a syndrome of *phenomenology* (thought and feeling qualities), *physiology* (neural, chemical, and other physical responses in the brain and body), *expressions* (signs of emotional state), *behaviours* (action tendencies or readinesses), and *emotivations* (characteristic goals that people want to attain when the emotion is experienced). Gendron and Barrett (Gendron & Barrett, 2009) similarly claim that emotions are comprised of subprocesses, including an affective and cognitive (e.g., situational construal) component, and are highly contextualized in nature. Common to all of these definitions is the idea that
emotions are an affective experience that can be characterized by physiological changes and defined by a cognitive construal of some kind. As states indexing occurrences of value, emotions have been proposed to carry functional value in physiologically preparing the body for action, permitting flexibility of behavioural responses to reinforcing stimuli, facilitating communication and social bonding, and influencing cognitive processes including evaluation, memory encoding, and memory recall (Rolls, 2000).

Motivations have been conceptualized as similar to emotions in that they also serve to define the relationship between the individual and the environment (Roseman, 2008), but differ from emotions in being more tightly linked to action and explicit goal associations: motivated action can be thought of as behaviour that is at least partly determined by a desired and hedonically laden end-state (i.e., it is goal directed. Pessoa (Pessoa, 2009) suggests that motivation can be commonly defined as what makes one work to obtain reward or to avoid punishment. Similarly, Roseman (Roseman, 2008) proposes that motivation is an internal state producing behaviour which moves the individual toward desirable reference values or away from undesirable reference values.

The present investigation begins with the hypothesis, based on these accounts, that emotion and motivation should be considered highly related but separate constructs at present (Chiew & Braver, 2011). One way to functionally differentiate these constructs and their putative effects on cognition comes from the social psychology literature and concerns emotion and motivation as they may relate to goal pursuit (Carver, 2006). While motivation may be the drive towards goal fulfillment, emotion may be emergent from one's sensed rate of progress towards goals; the difference between one's present status and one's goal state is experienced as affect and, if necessary, may signal the need for goal
reprioritization. In his ‘coasting hypothesis’, Carver proposes that positive emotion emerges from goal success at a rate faster than anticipated, acting as a signal that the organism may safely attend to other information (‘coasting on the present goal’; (Carver, 2003). In line with this viewpoint, positive emotion has been proposed to be a signal of safety in the environment, promoting free exploration and broadened thought (Fredrickson, 2004; Fredrickson & Branigan, 2005). This explanation has been used to account for extensive evidence that positive emotion may promote creativity and lead to broadened attention, relative to neutral or negative emotion (Fredrickson & Branigan, 2005; Isen & Daubman, 1984; Isen, Daubman, & Nowicki, 1987; Rowe, Hirsh, & Anderson, 2007).

Neural and Psychological Mechanisms of Positive Emotion

The neural mechanisms underlying positive emotion’s effects on cognition remain unclear. Different theories have been posited to explain these effects. One influential theory, the dopaminergic theory of positive affect (Ashby, Isen, & Turken, 1999), was developed to address findings that positive emotion is linked to broadened cognition. Ashby and colleagues extrapolated from literature on the neural substrates of reward processing to propose that the psychological effects of positive emotion are linked to increased dopamine (DA) release (via the substantia nigra and ventral tegmental area). The particular cognitive effects of increased DA release during positive affect were postulated to occur via projections to the anterior cingulate cortex (ACC) and striatum, with increased DA facilitating the ability of ACC and striatum to initiate a switch among active task sets, rules, or goal representations maintained in lateral prefrontal cortex (PFC). This facilitation of switching among task-set representations under positive affect enables unusual or non-
dominant sets to become active with a greater probability than under neutral affect conditions, facilitating creative problem solving. In connectionist simulations, the account was tested and exhibited an ability to account for certain behavioural performance patterns observed by Isen and colleagues under positive affect manipulations (i.e., improved performance on creative problem-solving and semantic association tasks; (Ashby et al., 1999; Ashby, Valentin, & Turken, 2002).

Dreisbach, Goschke, and Muller (Dreisbach, 2006; Dreisbach & Goschke, 2004; Muller et al., 2007) developed a related theoretical framework, which emphasizes that the cognitive flexibility associated with positive affect may have systematic costs in addition to the benefits posited by broadening theories. Specifically, Dreisbach proposed that the changes in dopamine activity triggered by positive affect lead to a shift in the balance between cognitive stability and cognitive flexibility, by increasing the tendency to update to new task goal representations and decreasing the tendency to perseverate in maintaining old ones. Empirical evidence from performance in set-shifting and context maintenance paradigms was consistent with this hypothesis, demonstrating positive affect induced facilitation of performance under conditions dependent on flexibility, but impairment under conditions stressing maintenance (Dreisbach, 2006; Dreisbach & Goschke, 2004).

In summary, these separate but similar theoretical accounts of the effect of positive emotion on cognition have tended to emphasize influences on cognitive flexibility, potentially by enhancing updating of goal information in working memory. Although most work has emphasized the adaptive value of such influences, it has also been suggested to come at a cost to goal maintenance. At the level of neural mechanisms, the focus has been
on the dopamine system and PFC, which, as is discussed next, has strong parallels to theoretical accounts regarding how motivation might modulate cognitive control.

*Neural and Psychological Mechanisms of Reward Motivation*

Theoretical accounts of motivation suggest a strong linkage to cognitive control and goal regulation (Carver & Scheier, 1998; Kruglanski, Shah, Fishbach, Friedman, & Chun, 2002; Simon, 1967): specifically, information processing accounts of higher cognition have emphasized that motivational signals may play a focused role in the prioritization, updating, and termination of goal representations that provide hierarchical control of behaviour (Simon, 1967). Over the last twenty years, the intrinsic relationship between motivation and goals has been a central focus of researchers primarily working within the social and individual differences tradition, based on the central claim that motivations are expressed primarily as the activation and representation of specific cognitive and behavioural goals over others (Kruglanski et al., 2002). Further work has been geared towards demonstrating that goal-directed behaviour can be primed and biased by implicit and/or subliminal motivational cues, suggesting a relatively direct route for motivation-cognition interactions (Aarts, Custers, & Veltkamp, 2008; Bargh, Gollwitzer, Lee-Chai, Barndollar, & Trotschel, 2001; Custers & Aarts, 2010). Recently, psychological theories postulating the role of motivation in activating goals and guiding behaviour have begun to be bridged with neuroscience-based studies to more clearly specify the biological mechanisms by which motivation might influence cognitive control.

A primary focus of neuroscience studies on motivation and cognitive control has been to demonstrate that these two processes are integrated within specific brain regions,
such as the lateral PFC. Early work involving single-unit recording in primates demonstrated that task-related neuronal activity in PFC was modulated by the expected reward value associated with performance (Leon & Shadlen, 1999; Watanabe, 1996; Watanabe, Hikosaka, Sakagami, & Shirakawa, 2002). In one compelling demonstration, it was found that reward value directly enhanced the fidelity of active maintenance in working memory (Leon & Shadlen, 1999). More recent studies carried out in human subjects using functional magnetic resonance imaging (fMRI) have used designs that orthogonally manipulate cognitive control demand and motivational value across a range of task domains, including working memory (Pochon et al., 2002), context maintenance (Kouneiher, Charron, & Koechlin, 2009; Locke & Braver, 2008), and selective attention (Padmala & Pessoa, 2011). These studies have confirmed the presence of specific regions within lateral PFC (along with effects in other associated regions, such as the ACC) that are sensitive to the interaction of the two factors, consistent with a specific role in integrating motivational and cognitive control functions.

The DA system also plays a central role in accounts of both motivation and cognitive control. Dopamine has long been thought to be a critical component of motivation and reward processing (Mirenowicz & Schultz, 1996; Robbins & Everitt, 1996; Schultz, 1998; Wise & Rompre, 1989). More recent accounts have suggested that DA shows phasic, cue-triggered responses to specific events that indicate reward availability (Montague, Dayan, & Sejnowski, 1996; Schultz, Dayan, & Montague, 1997) and/or high motivational salience (Berridge, 2007). In addition to accounts of phasic DA involvement in processing motivational incentives, a separate theoretical account has emphasized that the motivational utility of the current environmental context might be reflected in tonic, rather
than phasic, DA activation (Niv, 2007; Niv, Daw, Joel, & Dayan, 2007). Together, these accounts suggest DA activity will be increased both by transient cues and sustained contexts that indicate high reward or motivational value.

In addition to the literature indicating a link between DA and reward processing, a completely separate literature focused on the influence of DA release within PFC has suggested that the DA system provides a modulatory role in cognitive control functions. Neurophysiological studies in primates show that application of DA into PFC sharpens actively maintained stimulus representations (Arnsten, Cai, Murphy, & Goldman-Rakic, 1994; Sawaguchi & Goldman-Rakic, 1991; Sawaguchi, Matsumura, & Kubota, 1988). In contrast, DA antagonists reduce active maintenance-related PFC activity, and also cause behavioral impairments in working memory and cognitive control tasks (Sawaguchi & Goldman-Rakic, 1994; Sawaguchi, Matsumura, & Kubota, 1990; Williams & Goldman-Rakic, 1995). Similar effects have been observed in human pharmacological and fMRI studies, with DA agonists (administered systemically) being associated with improvements in working memory and cognitive control, and leading to associated modulations of PFC activity (Gibbs & D'Esposito, 2006; Kimberg, D'Esposito, & Farah, 1997). Linkages between the role of DA and PFC in motivation, and the effects of DA modulation on PFC-mediated cognitive control functions, have prompted the development of theories that explicitly link these two mechanisms. For example, the gating model account, put forward by Braver and Cohen (Braver & Cohen, 2000), emphasized the importance of phasic DA activity within PFC for the updating and active maintenance of goal representations. Specifically, this account suggests that the phasic DA responses to cues signaling reward prediction could also be exploited as a means of learning which task-related information should be actively
maintained in PFC, and when to update such information. In summary, these diverse perspectives pertaining to motivation and cognitive control generally suggest that reward incentives may promote maintenance and updating of goals and information in working memory, and that enhanced DA input to the PFC underlies this effect.

*Examining Emotional and Motivational Effects on Cognitive Control Dynamics*

The Dual Mechanisms of Control framework (Braver, Gray, & Burgess, 2007) has been put forward as a theoretical framework within which cognitive control mechanisms and dynamic shifts in these mechanisms as a result of various influences (including emotion and motivation) can be conceptualized. The present investigation used this theoretical framework to inform investigation of the effects of positive emotion and reward incentives on cognitive control. The DMC framework postulates that cognitive control can be understood as operating via two primary modes: proactive and reactive. Proactive control is thought to provide relatively tonic maintenance of goal information, while reactive control is thought to act as a flexible form of "late correction" in response to performance monitoring. These modes can be experimentally characterized by changes in cognitive performance and changes in temporal control dynamics.

Dreisbach and colleagues (Dreisbach, 2006; Dreisbach & Goschke, 2004) extended work on the broadening effects of positive emotion to this mechanistic realm, demonstrating that positive emotion was associated with greater cognitive flexibility and reduced maintenance (i.e., a shift towards increased reactive control). In contrast, reward-related enhancement in goal representations has been observed to manifest as a shift towards relatively greater proactive control (Chiew & Braver, 2013; Locke & Braver, 2008).
Several of these findings, providing indirect evidence of dissociable positive emotion and reward effects on proactive and reactive control mechanisms, have been demonstrated using the AX Continuous Performance Task (AX-CPT; J.D. Cohen & Servan-Schreiber, 1992; Servan-Schreiber, Cohen, & Steingard, 1996). Given its utility in measuring relatively separate indices of proactive and reactive cognitive control, and previous evidence that positive emotion and reward incentives have had opposite effects on cognitive control in separate studies using this paradigm, we used the AX-CPT in the present study as a task paradigm with which to directly compare the effects of positive emotion and reward on cognitive control within a single set of subjects.

On each trial, the AX-CPT presents participants with a cue, followed by a probe (e.g., letter stimuli presented one after the other), with participants responding to each cue-probe pair. One specific combination requires a target response (i.e., the letter ‘A’ followed by the letter ‘X’; AX trial) with all other cue-probe combinations requiring a non-target response. Target AX trials occur at high frequency (traditionally 70% of total trials), leading to high levels of interference in two low-frequency cue-probe combinations (10% each of total trials): AY (target cue, non-target probe) and BX (non-target cue, target probe). BY (non-target cue, non-target probe) trials also occur as a low-frequency (10% of total trials), non-target control condition. In AY trials, interference arises from cue-related expectancy and is thought to reflect proactive control, while in BX trials interference arises via a target response bias to the probe, reflecting reactive control.

AX-CPT performance under reward incentives (versus baseline) has been characterized by greater AY interference, reflecting enhanced cue maintenance and a shift to proactive control (Chiew & Braver, 2013; Locke & Braver, 2008). In contrast,
performance under positive mood induction relative to neutral has been characterized by greater BX interference, suggesting a shift to reactive control (Dreisbach, 2006). However, the conclusions that can be drawn from these studies are limited. No study combined investigation of both emotion and motivation manipulations. Both Chiew and Braver (2013) and Locke and Braver (2008) utilized a within-subjects design, as well as an experiment structure with both block manipulations of reward (i.e., a baseline vs. reward block) and trial manipulations of reward (incentive and non-incentive trials randomly intermixed within the reward block), allowing relative measures of both block (tonic) and trial (phasic) effects of incentive to be indexed. In contrast, Dreisbach (2006) used a between-subjects design to compare effects of positive versus neutral emotion manipulations on cognitive performance. Further, the manipulations used were trial-by-trial presentations of emotionally evocative stimuli, but since emotional valence was not manipulated on a within-subject basis, it is unclear whether the emotion effects observed in Dreisbach (2006) were tonic or phasic in nature.

Although prior studies do provide evidence consistent with the idea that positive emotion enhances cognitive flexibility and reactive control, the literature is not uniform in supporting this conclusion. For example, van Wouwe and colleagues (van Wouwe, Band, & Ridderinkhof, 2009) also sought to examine the effect of positive affect (versus neutral) on cognitive control with the AX-CPT paradigm, examining ERP activity as well as behavioral performance. Although there was some evidence that ERP components thought to reflect reactive control showed higher amplitudes in the positive condition, no significant changes in overt task performance as a function of emotional valence were observed. Experimental designs differed between van Wouwe (2009) and Dreisbach (2006): while both used
between-subjects designs, van Wouwe used emotionally evocative video clips to induce mood with no trial-based emotional stimuli, such as those Dreisbach used. Such differences make it unclear whether the diverging results reported by Dreisbach and van Wouwe are due to experimental design issues, or due to complexities in the effects positive emotion may have on cognition.

Another account departing from the idea that positive emotion promotes cognitive flexibility and reactive control comes from the social psychology literature. Aarts and colleagues (Aarts et al., 2008) suggest that positive affect may promote goal pursuit, even when not directly relevant to the goal. Further, such affect is proposed to be the mechanism making the link between motivation and goal pursuit possible, even in the absence of conscious awareness. Observations that coactivation of a neutral goal concept and positive affect can lead to unconscious goal pursuit (Custers & Aarts, 2005) provide evidence in support of this proposal and lead to an alternative hypothesis that positive emotion may support goal-related, proactive control instead.

As this overview makes clear, experimental evidence provides mixed predictions regarding how positive emotion and reward incentives may compare in terms of their influence on cognitive control. Current experimental evidence that reward incentives promote proactive control is relatively robust and consistent with conceptions of incentives as relevant to/promoting goal maintenance. In contrast, previous studies examining positive emotion effect suggest multiple possible hypotheses: that relative to neutral, positive emotion may (1) promote cognitive flexibility and reactive control; (2) result in a null effect on performance (and possibly pupil dilation as well); or (3) promote goal pursuit and proactive control. These diverging hypotheses and the circumstances
under which each may best reflect interactions of affect and cognition remain yet to be clarified.

Using Pupillometry to Examine the Temporal Dynamics of Cognitive Control

We were interested in using pupillometry in the present study to delineate the time courses of emotion/motivation-cognition interactions during performance of the AX-CPT. Previous work from our laboratory has suggested that pupillometry may successfully index changes in cognitive control dynamics as a result of incentive (Chiew & Braver, 2013); in particular, increased preparatory pupil activity during cue maintenance was observed under incentive relative to non-incentive conditions. This observation occurred prior to response on each trial and could not be indexed using overt performance measures, demonstrating the utility of pupillometry measures as a supplement to task performance in investigating the temporal dynamics of cognitive control.

Pupil diameter is determined by the relative contraction of two opposing sets of muscles within the iris of the eye (Beatty & Lucero-Wagoner, 2000) that are sensitive to sympathetic and parasympathetic nervous system activity (Steinhauer, Siegle, Condray, & Pless, 2004). While changes in pupil diameter are determined primarily by light and accommodation reflexes, the pupil also demonstrates tiny, cognitively related fluctuations in pupil diameter independent of visual luminance levels, which have been well-established as indexing fairly specific changes in cognitive demand and effort (Beatty, 1982a, 1982b; Granholm, Asarnow, Sarkin, & Dykes, 1996) as well as cognitive fatigue (Fukuda, Stern, Brown, & Russo, 2005; Sirevaag & Stern, 2000). Evidence for this phenomenon was originally observed by Beatty and colleagues, who reported increasing pupil diameter with
increased memory load (Kahneman and Beatty, 1966) and arithmetic demands (Ahern and Beatty, 1979). More recent evidence using visual luminance and pharmacological manipulations suggest that such changes in pupil dilation as a result of cognitive demands may reflect inhibition of parasympathetic activity with task engagement (Steinhauer et al., 2004). With technology permitting collection of pupillary data at a high temporal resolution, interest in pupillometry as a time course measure of cognitive control has been growing, following work suggesting that it may index changes in cognitive control dynamics related to typical development (Chatham, Frank, & Munakata, 2009) and decision-making (Satterthwaite et al., 2007).

Separate from these findings, pupil diameter has also been shown to be responsive to emotional arousal associated with sympathetic nervous system activity when viewing emotionally evocative stimuli without engaging in a cognitive task (Bradley, Miccoli, Escrig, & Lang, 2008). This joint sensitivity to affective and cognitive influences suggests that pupillometric methods may be ideal for investigating the dynamics of emotion and motivation-cognition interactions. Research on this question is still in its early stages: it is not well understood how activity in the sympathetic system as a result of changes in emotional arousal and inhibition of the parasympathetic system as a result of changes in cognitive processing may work together to determine changes in pupil dilation during affect-cognition interactions.

Pupil activity as an index of cognitive processing can be broken down into phasic and tonic components. In this context, phasic pupil activity refers to task-evoked pupillary responses, in which pupil dilation is time-locked and measured in response to an eliciting event of interest, and where dilation is measured in terms of percent change relative to a
pre-stimulus baseline. Tonic pupil activity, which is thought to reflect more sustained processes as opposed to transitory, trial-evoked processes, has been measured via pupil diameter using different methods. These include examining pupil diameter prior to task performance (i.e., a pre-experimental baseline; [Heitz, Schrock, Payne, & Engle, 2008]) or as an average measure of diameter at inter-trial interval (ITI) periods (as done in [Chiew & Braver, 2013]). The latter method was used in the present study to compare tonic pupil activity as a function of task context (task block). It has been suggested that these components may reflect distinct processes: tonic pupil size may reflect arousal state, while phasic pupil dilation may reflect cognitive and emotional processes but be less sensitive to general arousal ([Granholm & Steinhauser, 2004]).

A more recent account has also emphasized theoretical and neurocomputational distinctions between tonic and phasic pupil activity, specifically postulating that these reflect distinct modes of norepinephrine-mediated function. This account proposes that beyond being simple indicators of autonomic arousal, temporally distinct tonic and phasic components of the pupil signal may specifically reflect distinct control modes modulated by the locus coeruleus-norepinephrine system ([Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010]). The adaptive gain theory of locus coeruleus function posits that control depends on the balance between exploration and exploitation in pursuit of rewards, and that these states relate to tonic and phasic norepinephrine (NE) release, respectively ([Aston-Jones & Cohen, 2005]). The exploration/exploitation balance refers to the tradeoff between pursuing new sources of reward (exploration) versus staying with and maximizing currently known sources of reward (exploitation), and is thought to operate at all levels of behavioural decision-making, from the very simple to the very complex.
In recent work, Gilzenrat et al. (2010) reported findings suggested that sustained and transient pupil activity reflects these distinct components of NE release: specifically, they argued that reduced tonic/increased phasic pupil activity related to exploitation and task engagement, while increased tonic/reduced phasic pupil activity related to exploration and task disengagement. In our present dataset, we wanted to examine tonic and phasic pupil activity and how pupil dynamics might shift as a function of emotional and motivational manipulations, relating them to these NE-mediated control states. However, we also expected that changes in tonic and phasic pupil activity in the present study would be more complex than a pattern reflecting a NE-mediated exploration/exploitation tradeoff alone (i.e., inverse relations between tonic and phasic pupil activity), given extensive experimental evidence that dopamine plays a major role in reward processing. While central dopamine activity has been associated with spontaneous blink rate (Karson, 1983; Taylor et al., 1999), to our knowledge there is no published literature at present examining dopaminergic contributions to pupil dilation. Thus, how dopamine may interact with norepinephrine in the present experimental paradigm and how that might be reflected in pupil activity is unknown.

*Individual Difference Measures and Cognitive Control*

A secondary approach used in the current study was to examine the role of individual differences in mediating the effect of emotional/motivational influences in cognitive control. Examination of individual differences has a long research tradition in the investigation of personality and of psychopathology, but has emerged more recently as a fruitful research approach in experimental studies of cognitive processes, where traditional
focus has been on effects of experimental manipulation, pooled across individuals. As recent reviews suggest (Braver, Cole, & Yarkoni, 2010; Yarkoni & Braver, 2010), examination of individual differences, especially in combination with cognitive neuroscience methodologies, has helped inform mechanistic accounts of executive control. For example, individual differences in working memory capacity have been found to be associated with interactions between prefrontal attentional filtering mechanisms and WM storage-related parietal activity (Edin et al., 2009). Individual differences in trait anxiety have been associated with variation in the relative balance of proactive and reactive cognitive control (Fales et al., 2008). Additionally, differences in personality and affective factors have been shown to account for variation in the behavioural and neural effects of emotion and motivation-cognition interactions (Canli et al., 2001; Jimura, Locke, & Braver, 2010; Krug & Carter, 2010; Locke & Braver, 2008). Combining individual differences measures with task performance and neural data has been an important experimental approach in cognitive neuroscience over recent years, but to our knowledge, a similar approach has not yet been utilized with pupillometric data. Given pupillometry's utility as a high temporal resolution measure of cognitive dynamics, but outstanding ambiguity about the nature of the pupil signal, an individual differences approach could be useful in characterizing underlying mechanisms contributing to pupil response. We thus investigated whether an individual differences approach led to interpretable relationships in the current dataset.

Comparing Emotional and Motivational Influences on Cognitive Control: Approach of the Current Study
In the present study, we had two major aims. The first aim was to test whether effects of positive emotion and reward motivation were distinct, by conducting a within-subjects investigation comparing the effects of these two manipulations on cognitive control performance. As a measure of cognitive control we used the AX-CPT, since it permits examination of shifts between relatively more proactive and reactive modes of cognitive control. Task performance, as well as pupil dilation as an independent measure of mental effort, was used to examine the effects of these manipulations.

The present study follows Chiew and Braver (2013) in utilizing a mixed block/event experimental design to examine emotional and motivational effects. Positive emotion and motivation manipulations were administered in two separate experimental sessions. We will outline design for the reward motivation manipulation, with emotion manipulation design in parentheses: in each session, participants perform separate baseline (neutral; no emotional stimuli or incentives) and reward (emotion) blocks. Within the reward (emotion) block, incentive (emotional) trials are randomly intermixed with non-incentive (neutral) trials. This design permits examination of both trial-based effects (i.e., contrasting incentive and non-incentive trials within the reward block / neutral and positive trials within the positive emotion block) and block-based effects (i.e., contrasting baseline block trials with non-incentive trials in the reward block / neutral block trials with neutral trials within the positive emotion block) of incentive/emotion on task performance. Prior evidence suggests that these contrasts may index transient and sustained (i.e., block-based) motivational influences on cognitive control (Jimura et al., 2010; Chiew and Braver, 2013); it has yet to be determined whether emotional influences on cognitive control can be characterized via these distinct temporal dynamics or not.
This experimental design, which permits dissociation of block and trial-based (i.e., tonic and phasic) effects of incentive, dovetails nicely with experimental evidence that tonic and phasic pupil activity may reflect distinct control processes and allows examination of whether distinct tonic and phasic emotion and incentive effects impacted temporally distinct components of the pupil response and/or caused pupil activity dynamics to shift. Previous evidence suggested that incentive was related with both tonic and phasic changes in pupil activity (Chiew and Braver, 2013): block-based incentive effects (baseline vs. non-incentive trials) were associated with increased tonic pupil activity, but decreased phasic activity; increases in both tonic and phasic pupil activity were observed in incentive trials. This pattern is somewhat consistent with Gilzenrat’s findings, in that tonic and phasic pupil activity were inversely correlated and related to different control states. However, our prior findings provide hints that other influences besides norepinephrine, such as dopamine, may be present as well. The present study did not explicitly investigate neuromodulatory influences on cognition and pupil activity, but investigated whether patterns of tonic / phasic pupil activity were similar to Gilzenrat’s results or our previous results (which provided evidence for influences beyond NE). Importantly, we investigated whether shifts between tonic and phasic pupil activity were similar under incentive and positive emotion, providing another basis of comparison between emotion and motivation influences on behaviour.

In the present study, using task performance and pupillometric measures together permitted testing of the following hypotheses, based on prior experimental findings: (1) that reward incentives would be associated with enhanced proactive control (as reflected in a decrease in AY trial performance and enhancement in performance in all other trial
types) along increased preparatory pupil dilation during AX-CPT performance; (2) that positive emotion would be associated with either: a) enhanced cognitive flexibility / reactive control (as reflected in enhanced AY trial performance; in line with Dreisbach's findings); b) enhanced proactive control (as reflected in a decrease in AY trial performance / enhancement in performance in all other trial types; in line with Aarts and Custers' findings), or c) no change in maintenance-related performance or pupil activity (consistent with Van Wouwe's findings).

To provide a manipulation check, we used self-report measures of emotion effects as well as an examination of pupil responses during passive viewing the emotional visual stimuli in a separate run (i.e., independent of the AX-CPT), which was modeled after the protocol used in Bradley et al. (2008). Bradley and colleagues observed that viewing positively valenced pictures was associated with greater pupil dilation than viewing neutrally valenced pictures (owing to heightened autonomic arousal). Thus, this component of the study was included to validate whether the emotional images that we used were effective in evoking emotional arousal (i.e., relative to neutral images).

The second primary aim of the present study was to examine the role of individual differences in mediating the effect of emotional/motivational influences in cognitive control. Specifically, we investigated whether individual differences variation, in both personality and cognitive measures, might provide additional leverage in understanding the common or distinct effects of reward motivation and positive emotion. In order to reliably examine individual difference questions, a relatively large participant sample (N=100) was collected that enabled adequate statistical power\(^1\) (calculated using G*Power

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\(^1\) 0.95 power to detect small-to-medium effects (\(\rho=0.035\)) in two-tailed bivariate correlations (N=100)
Specifically, we examined whether task performance and pupil dilation could be related to each other on an individual subject level in a meaningful way, and whether individual differences in personality, affect and cognitive variables could be meaningfully related to task performance, task-related pupil dilation, and interactions between affective factors and cognition. The following hypotheses were tested regarding stable individual differences: (1) that reward-related personality differences would influence the extent to which participants’ performance and pupil activity changed under incentive manipulations (i.e., more highly reward-sensitive individuals would show greater increases towards proactive control and increases in preparatory pupil dilation with incentive); (2) that the extent to which positive emotion is induced (as assessed by self-report) would relate to positive affect/reward-related personality differences and influence the extent to which performance/pupil activity changed under emotion manipulation; (3) that working memory capacity would be positively correlated with proactive control and task-related pupil activity during the AX-CPT, independent of emotion/reward manipulations (following previous experimental observations by Heitz et al., 2008); (4) that trait anxiety would be negatively correlated with proactive control, independent of emotion/reward manipulations (following previous experimental observations by Fales et al., 2008).

Methods

Participants

One hundred and twelve healthy young adult participants took part (61 female; mean age 21.0 years +/- 0.27). Participants were recruited from volunteer pools
maintained by the Department of Psychology at Washington University in St. Louis and from the St. Louis community using posted advertisements. All participants were right-handed, had corrected-to-normal vision, and were free from psychiatric or neurological disorders. Informed consent was observed from all subjects prior to participation, in accordance with the human subjects guidelines established by Washington University. Participants performed the experiment for a $10/hour payment, plus an additional monetary bonus in the Reward session due to reward incentives. Although participants were not informed of this until the end of the Reward session, the bonus was a fixed amount ($5). Of the one hundred and twelve subjects collected, one hundred had usable data (i.e., attended both experimental sessions) to be included in analyses (51 female; mean age 21.1 years +/- 2.9). Within this N=100, certain portions of data were missing or not usable for every analysis, so not every participant could be used in every analysis (N noted for each analysis). In particular, 20 participants had one or more runs of pupil data that was unusable due to poor data quality but intact task performance data, leaving N=80 with full pupillometric data (42 female; mean age 21.2 +/- 2.9). Slightly larger numbers had complete Emotion session pupil data (N=92, 48 female; mean age 21.0 +/- 2.8) and complete Reward session pupil data (N=89; 44 female; mean age 21.2 +/- 3.0).

General Study Structure

A general schematic of the study structure is shown in Figure 1. Participants were seen in two separate sessions (Emotion and Reward; order counterbalanced) where they completed the AX-CPT paradigm while pupil diameter data was collected using an infrared eye tracker. In the Emotion session, participants performed two 200-trial blocks of the AX-
CPT in static order: one block under Neutral emotion induction, followed by one under Positive emotion induction. Each block was preceded by a brief video clip intended to induce the appropriate emotion (either neutral or positive; similar manipulation to van Wouwe et al. (2009), who used emotionally evocative video clips prior to task block as a mood manipulation, with stimuli used previously by (Gray, 2001)). During the task block, participants viewed a valenced image from the International Affective Picture System (IAPS; (P.J. Lang, Bradley, & Cuthbert, 1999) as a precue to each trial. This precue manipulation followed the trial-by-trial emotional stimuli used by Dreisbach (2006), where positive and neutral emotion inductions led to differing patterns of cognitive control. In the Neutral block, all precue images were neutrally-valenced, while in the Positive block, positive and neutral precue images (50% each) were randomly intermixed. This manipulation differed from designs by both van Wouwe and Dreisbach, who did not manipulate emotion valence on a within-subject basis.

In the Reward session, participants again performed two 200-trial blocks of the AX-CPT in static order: one block under Baseline conditions (i.e., no reward incentives provided), followed by one block under Reward conditions (i.e., reward incentives provided). In the Reward block, incentive and non-incentive trials (50% each) were randomly intermixed. Following the experiment structure of the Emotion session, participants viewed a video clip prior to each task block: these video clips were neutrally-valenced in nature (again, as used in Gray, 2001). During the task block, participants viewed an image from the IAPS stimulus set as a precue to each trial: in the Reward session, two neutrally-valenced IAPS images chosen from those used by Dreisbach (2006) were used (image selection randomized across participants): participants were told these
images were meaningless in the Baseline block, while in the Reward block one image served as an incentive cue and one image served as a non-incentive cue, signifying the presence or absence of incentive on each trial. Across the two sessions, three neutrally valenced video clips and one positively valenced video clip were used for each participant. Order of clips was counterbalanced across participants, and there were no repeated viewings of any clips (i.e., three different neutral clips were used for each subject). All clips were approximately 10 minutes in length, and no significant differences in performance were observed as a result of the counterbalancing of video clip presentation.

Figure 1. General schematic of study structure. Participants came for two experimental sessions: the Emotion session (AX-CPT under neutral and positive emotion conditions) and the Reward session (AX-CPT under baseline and reward conditions). The Self-Assessment Manikin (SAM) was administered at intervals throughout the sessions, and passive viewing of IAPS images was administered following the emotion AX-CPT task runs. Individual difference questionnaires were completed between sessions, and further individual difference measures (pupil diameter at fixation, WMC, and WRAT) were collected after the reward AX-CPT task runs.

For task trials in both Emotion and Reward sessions, participants were presented with a cue-probe letter combination following the precue. Participants were required to
respond to this combination and viewed a feedback screen based on their performance. More specific information about trial structure and timing is included below in the *AX-CPT Paradigm* section.

Before and after each video clip and task block (i.e., five times in total during each experiment session), participants’ emotional state was assessed using Bradley and Lang’s Self Assessment Manikins (SAM; a brief, non-verbal measure of the pleasure, arousal, and dominance associated with a person's affective reaction; (Bradley & Lang, 1994). More specific information about SAM rating administration is included below in the *SAM Assessments* section.

In the Emotion session, following the AX-CPT blocks, participants completed a passive viewing task of positive and neutral IAPS images (both those viewed in the AX-CPT and novel images) to gain a control measure of pupil activity related to emotional arousal independent of cognitive demands (in a similar manner to (Bradley et al., 2008). This was followed by a brief recognition memory test. In the Reward session, following the AX-CPT blocks, participants took part in a 2-minute fixation run to collect pupil data and an estimate of blink rate at rest. Following the fixation run, participants completed the O-SPAN and the WRAT tests (see *Individual Difference Measures*).

The two sessions were conducted on separate visits, a maximum of one week apart. Upon completion of the first session, participants were presented with a packet of pen-and-paper questionnaires measuring individual differences (see *Individual Difference Measures*) and asked to complete and return them at the second session. Participants were paid $5 for completion of the questionnaires in addition to receiving $10/hour pay for experiment participation in the lab. At the end of the two sessions, participants were fully debriefed.
SAM Assessments

Subjective emotional experience was assessed over the course of the experiment with the Self-Assessment Manikins (SAM; Bradley & Lang, 1994), administered by computer. Each SAM assessment required participants to rate the valence and arousal of their currently experienced emotional state. Both valence judgments and arousal judgments were made on a 5-choice scale, with “manikins” (non-verbal characters) illustrating the choices. On valence these ranged from 1 (very negative) to 5 (very positive) with 3 (i.e., middle score) being neutral. On arousal, these ranged from 1 (no/very low arousal) to 5 (very high arousal) with 3 being moderate arousal. Participants made five SAM ratings over the course of each experimental session. Thus, in the Emotion session, participants made SAM ratings (1) upon arrival (i.e., at baseline); (2) after watching a ~10 minute neutrally-valenced video clip; (3) after completing the Neutral block of the AX-CPT; (4) after watching a ~10 minute positively valenced video clip; (5) after completing the Positive block of the AX-CPT. In the Reward session, participants made SAM ratings in a similar manner, i.e., (1) upon arrival (i.e., at baseline); (2) after watching a ~10 minute neutrally-valenced video clip; (3) after completing the Baseline block of the AX-CPT; (4) after watching a different ~10 minute neutrally-valenced video clip; (5) after completing the Reward block of the AX-CPT.

AX-CPT Paradigm

The AX-CPT consists of a series of continuous trials in which single letters are presented in cue-probe sequences. One specific cue-probe trial sequence requires a target response (i.e., ‘A’ followed by ‘X’; AX trial), with all other combinations of letters requiring a
non-target response. The AX target trial type occurs with 70% frequency, and is randomly intermixed with three types of non-target trials, each occurring with 10% frequency: AY (target cue, non-target probe), BX (non-target cue, target probe), and BY (non-target cue, non-target probe). Besides A and X, the stimuli that were used as ‘B’ and ‘Y’ (non-target) stimuli were the letters B, D, E, F, G, M, P, S, U, Y, and Z.

Trial structure is shown in Figure 2. Each trial began with a 1000 ms precue: an image from the IAPS stimulus set. In the Neutral block of the Emotion session, the IAPS images used were neutrally-valenced, and in the Positive block of the Emotion session, the IAPS images used were neutrally and positively-valenced, randomly intermixed (50% of trials each). IAPS images used followed Dreisbach (2006). In both task blocks of the Emotion session, participants were told to observe the precue image as it appeared, but not to respond. In the Reward session, two neutrally-valenced IAPS pictures (chosen from those used in Dreisbach, 2006; randomized across participants) were presented as precues. In the Baseline block of the Reward session, participants were told that the precues were meaningless; in the Reward block, participants were informed that the precues signified non-incentive and incentive trials, respectively.

Following the precue, the contextual cue (e.g., ‘A’) appeared for 1000 ms, presented centrally in white on a black screen (Arial font, size 42). The contextual cue was followed by a 1500 ms fixation cross, and then a probe letter appeared in the same font (e.g., target probe was ‘X’) for 1000 ms, during which time the participant was required to respond to the cue-probe combination (indicating whether it was a target or non-target trial).

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2 Neutrally-valenced images used in the AX-CPT were: 7000.BMP, 7002.BMP, 7004.BMP, 7006.BMP, 7009.BMP, 7010.BMP, 7020.BMP, 7025.BMP, 7030.BMP, and 7034.BMP. Positively-valenced images used in the AX-CPT were: 1440.BMP, 1463.BMP, 1710.BMP, 2050.BMP, 2057.BMP, 2058.BMP, 2250.BMP, 2311.BMP, 2341.BMP, 2345.BMP
Following probe presentation, a feedback screen appeared for 1000ms. In the Emotion session (for both Neutral and Positive blocks), the feedback message read ‘Trial Over’ if the participant had answered correctly and ‘Error’ if the participant had answered incorrectly. This pattern of feedback was also provided in the Baseline block of the Reward session. In the Reward block of the Reward session, the feedback pattern varied with trial incentive status. In incentive trials within the Reward block, the feedback message read ‘You Won a Bonus!’ if the participant had replied accurately and under reaction time (RT) cutoff (i.e., meeting reward criteria), ‘Trial Over’ if the participant had replied accurately but slower than RT cutoff, and ‘Error’ if the participant had made an error. Each participant's RT cutoff for reward receipt was individually determined from baseline block performance (explained further in Procedure below). Trials were separated by an inter-trial-interval (ITI) of 4000ms.

Figure 2. Trial structure. In Neutral block trials, only neutral IAPS images were presented. In Positive block trials, neutral and positive IAPS images were randomly intermixed and presented. In Baseline and Reward block trials, only two IAPS pictures were presented per participant (chosen via random counterbalance): the participants were told in the Baseline block that these images had no meaning, and then in the Reward block they were explicitly informed that which image signified an incentive trial and which did not.
Passive Viewing Run (in Emotion Session)

Following completion of the AX-CPT blocks in the Emotion session, participants completed a block of passive viewing of IAPS images. This run was included to examine the extent to which pupil dilation occurred due to emotional arousal when viewing valenced versus neutral images, in a context relatively free of cognitive task-evoked activity (following experimental procedure used by Bradley et al., 2008). Half of the images were old (previously seen in the AX-CPT blocks) and half were novel; the novel images, like the previously-seen ones were an equal mixture of positive and neutral valence\(^3\). Average normed valence and arousal of the novel images was matched to the images previously viewed during the AX-CPT (refer to Table 1 for normed values). All four image types (pos/neu x old/new) were randomly intermixed. Following trial structure in Bradley et al. (2008), participants viewed each image for 6 seconds, with a 10-second ITI between them. Before each picture, a grayscale slide of mean luminosity (computed across all IAPS images shown in the run) was shown for 2 seconds to control illumination level prior to picture onset.

Participants were told that their memory for the passively viewed images would be tested immediately after (to ensure that participants attended the images); a brief, self-paced recognition memory run consisting of ten images (five presented in the passive viewing run, five novel) was administered following the passive viewing run but was not scored for performance.

\(^3\) The novel IAPS images used in the passive viewing run were as follows: 2840.BMP, 5534.BMP, 7036.BMP, 7160.BMP, 7161.BMP, 7175.BMP, 7217.BMP, 7235.BMP, 7491.BMP, 7950.BMP (neutral valence); 1600.BMP, 1610.BMP, 1920.BMP, 2071.BMP, 2170.BMP, 2209.BMP, 2550.BMP, 2660.BMP, 5831.BMP, 5910.BMP (positive valence).
Table 1. Norms of IAPS images used in IAPS passive viewing run (taken from (P.J. Lang et al., 1999). Task Usage status indicates whether images were “New” (i.e., novel) or “Old” (i.e., previously viewed during the Emotion session AX-CPT) at the time of the passive viewing run. Normed valence and arousal ratings were collected on a 9-point Likert scale: for valence, this scale went from most negative to most positive, with 5 connoting a neutral valence; for arousal, this scale went from lowest to highest arousal level.

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Fixation Run with Pupillometry

Following completion of the AX-CPT blocks in the Reward session, participants completed a 2-minute block of resting fixation to measure pupil dilation and blink rate at rest. They viewed a centrally-presented fixation cross (white Arial font, size 42, on a black screen) and asked to fixate while pupil data was collected with the eyetracker camera. This data was collected to gain a rough estimate of participants’ blink rates at rest to be used as an exploratory correlate with performance, given evidence that blink rate may be an indirect measure of dopamine activity (Taylor et al., 1999). However, this data was not analyzed at this time.

Apparatus

The experimental paradigm was presented using E-prime (Psychology Software Tools, Inc., Pittsburgh, PA) on a Dell PC computer. Participants were seated in a chair with a headrest supporting the back of the head to minimize motion and viewed the paradigm on a computer monitor. Accuracy and reaction time (RT) was collected using an E-prime Button Box connected to the stimuli computer.

Pupillometry Data Collection

Pupil data were collected as participants completed the task using an Eyelink 1000 infrared eye tracker (SR Research Ltd., Mississauga, ON) running Eyelink software (version 4.48), sampling at 1000Hz and at spatial resolution < .01° RMS. Calibration and validation of gaze direction were conducted before each experimental run. Pupillometry data were preprocessed using in-house software written in Java (Oracle Corporation, Redwood
Shores, CA). Blinks were corrected for using linear interpolation. Only correct response trials were included for pupillometric analysis (there were too few errors to analyze separately). For examinations of transient (trial-related) effects, we examined each trial’s pupil activity, normalized as a percent change from a baseline period (100ms of ITI prior to each trial onset), while for examinations of sustained (block-related) effects, we examined pupil activity in Eyelink’s scaled pupil diameter values rather than absolute sizes – scaled values generally range between 3000-7000 (corresponding approximately to 3-7mm; following (Marshall, 2007).

Data Analysis: Task Performance

Behavioural performance data was analyzed with separate repeated-measures ANOVAs conducted on error rates and median correct RTs as dependent variables. We conducted parallel analyses to compare block and trial-related effects of emotion and motivational incentive on task performance in the Emotion session and Reward session, respectively.

We also calculated and conducted analyses on a behavioural variable called the proactive index. The proactive index is a standardized score calculated on RTs and error rates that measures the relative tendency towards proactive control. For RTs, the proactive index was calculated as (AY-BX)/(AY+BX). For errors, the same equation was used, but correction had to be applied when error rates were equal to zero as follows: (error + 0.5)/(frequency of trials + 1). The proactive index calculation yields a score between -1 and +1: the closer a score is to +1, the more proactive task performance is considered to be.
To examine the block-related incentive effect on performance (in the Reward session), we conducted a 2 x 2 x 2 ANOVA on non-incentive trials with block (baseline, reward), contextual cue (A, B), and probe (X, Y) as within-subject factors. By including only non-incentive trials in this analysis, one can examine the block-based effect without the specific effect of trial-by-trial incentive. To examine the trial-based incentive effect on performance (in the Reward session), we conducted a 2 x 2 x 2 ANOVA on trials within the reward block, with trial-type (incentive, non-incentive), contextual cue (A, B) and probe (X, Y) as within-subject factors. We also compared proactive index measures as a function of incentive at both the block level (baseline versus non-incentive conditions) and the trial level (non-incentive versus incentive conditions), using both RTs and error rates, using paired-sample t-tests.

Analysis of task performance data for the Emotion session followed a similar structure. To examine the block-related mood effect on performance (in the Emotion session), we conducted a 2 x 2 x 2 ANOVA on neutral trials (i.e., trials preceded by a neutrally-valenced IAPS image) with block (neutral, positive), contextual cue (A, B), and probe (X, Y) as within-subject factors. To examine trial-based emotion effect on performance (in the Emotion session), we conducted a 2 x 2 x 2 ANOVA on trials within the positive block, with trial valence (neutral, positive), contextual cue (A, B), and probe (X, Y) as within-subject factors. Similarly to the analyses with Reward Session data, we compared proactive index measures as a function of positive emotion at both the block level (neutral block versus neutral trials in the positive block) and the trial level (neutral trials in the positive block versus positive trials), using both RTs and error rates, using paired-sample t-tests.
Data Analysis: Pupillometric Measures

To examine the effect of experimental manipulations on pupillometric data, pupil activity (extracted both as raw measures and percentage change measures from a baseline) was averaged within specific time-windows during the trial and subjected to analysis. For analyses of the sustained emotional and incentive effects, pupil activity (in raw measures) was examined at a 200 ms ITI period just prior to each trial's onset in order to examine tonic, rather than task-evoked, pupil activity as a function of block (comparing between neutral and positive blocks in the Emotion session, and baseline and reward blocks in the Reward session). For analyses of transient emotion and incentive effects, average magnitudes of pupil dilation (extracted as a percentage change measure from 100-ms pretrial baseline period) were calculated for a 250 ms period of interest within the trial, during cue maintenance just prior to probe onset (referred to as pre-probe onset, timepoints 2550-2800ms). These magnitudes were used to contrast non-incentive versus incentive trials within the reward block, and neutral versus positive trials within the positive affect block.

Average magnitudes of pupil dilation from these time periods of interest were examined using repeated-measures ANOVA in analyses analogous to those described previously for behavioural performance data. However, because the analyses of transient effects examined a period prior to probe onset, the ANOVA excluded the probe factor, because prior to probe onset, trial-type could not be classified (i.e., in analyses of Reward session data, incentive trial and contextual cue were the only two factors; in analyses of Emotion session data, emotional valence and contextual cue were the only two factors). Similarly, because analyses of sustained effects involved the time window prior to trial
onset, only block (baseline vs. reward, or neutral vs. positive affect), was included as a factor.

**Individual Difference Measures**

Participants completed several individual difference measures hypothesized to index possible influences on emotion and motivation-cognition interactions. Several of these measures were administered by pen-and-paper questionnaire: at the end of their first experimental session, participants were given a packet of individual difference questionnaires and were asked to complete them and bring them to their second experimental session. These questionnaires, which will be described subsequently, included the Generalized Reward and Punishment Expectancy Scales (GRAPES; (Ball & Zuckerman, 1990), the Regulatory Focus Questionnaire (RFQ; (Higgins et al., 2001), the State-Trait Anxiety Inventory (STAI; (Spielberger, 1985), the Positive and Negative Affect Scales (PANAS; (Watson et al., 1988), the Behavioural Inhibition System/Behavioural Activation System Scales (BIS/BAS; (Carver & White, 1994), and the NEO Five Factor Inventory (NEO-FFI; (Costa, 1992). In addition, at the end of the Reward session (following AX-CPT performance and resting pupil run), participants completed the Automated Operation Span Task (O-SPAN; (La Pointe & Engle, 1990; Unsworth, Heitz, Schrock, & Engle, 2005) by computer, and the Wide Range Achievement Test (Jastak & Wilkinson, 1984), which was administered by the experimenter and completed using pen-and-paper.

The GRAPES, BIS/BAS, and RFQ scales aimed to assess individual differences in reward sensitivity/anticipation, which previous evidence suggests may be related to incentive-related changes in cognitive control (Locke, 2008). The NEO assesses individual
differences in the five factors of personality (Neuroticism, Extraversion, Openness to Experience, Agreeableness, Conscientiousness), which have been associated with stable differences in emotionality (with neuroticism and Extraversion associated with negative and positive affect, respectively (Tellegen, 1985; Watson & Clark, 1984), and the PANAS assesses relative positive and negative affect; these individual differences may have influenced the effectiveness of the emotion and/or motivation inductions. The STAI assesses individual differences in anxiety (both state and trait), which previous evidence suggests is related to cognitive efficiency and cognitive control [i.e., higher anxiety has been correlated with decreased proactive but increased reactive control (Fales et al., 2008), while trait-specific anxiety has been associated with increased negative emotional interference on an emotional conflict task (Krug & Carter, 2010)]. Thus, anxiety measures were taken with the aim of helping account for individual variance in baseline task performance, as well as possibly predicting tendencies towards negative affect, in our participant sample. The O-SPAN and WRAT assess general cognitive performance: the O-SPAN assesses working memory capacity (WMC) and the WRAT assesses reading comprehension/mathematical problem solving as a general proxy for an IQ test. These tests were administered with the aim of helping account for individual variance in baseline task performance. For example, WMC has been associated with goal maintenance / context processing ability (Redick & Engle, 2011) and pupillometric evidence suggests that low WMC individuals may have lower pupil diameter in baseline conditions than high WMC individuals, but under incentive conditions may show similar increases in pupil dilation, exerting similar or even greater amounts of cognitive effort to gain rewards (Heitz et al.,
2008). WRAT was measured as a second, exploratory measure of cognitive ability but the data was not analyzed in the present investigation.

**Results**

*Effects of Emotion Inductions: SAM Assessments*

Subjective emotional experience was assessed over the course of the experiment with the Self-Assessment Manikins (SAM), administered by computer. As mentioned in the Methods section, participants completed five SAM assessments, consisting of a valence and an arousal judgment, over the course of each of the two experimental sessions (i.e., ten assessments in total). Average valence and arousal ratings for participants with complete SAM data (N=97) are shown in Figure 3.

Figure 3. Average (a) valence and (b) arousal SAM ratings for the Emotion and Reward sessions (five intervals per session, as specified in on the X-axis). For valence (Figure 3a), higher values on the Y-axis indicate a more positive valence.

Separate repeated-measures ANOVAs were conducted on the SAM ratings for valence and arousal, with session and time interval as within-subjects factors and session order (Emotion first and Reward second, or vice versa) as a between-subjects factor. For valence, the ANOVA revealed a significant main effect of session [$F(1,95) = 4.478$, $p = .037$].
a significant main effect of time \[ F(4,380) = 38.865, p < .001 \], and a significant session x time x order interaction \[ F(4,380) = 3.055, p = .017 \]. Within-subjects simple contrasts were utilized to clarify these significant effects further. The session x time x order interaction was due to the fact that rated valence over time (i.e., over the five rating intervals of each experimental session) differed more as a function of session order in the Emotion session [where the time x order interaction was \( p = .101 \)] than in the Reward session [where the time x order interaction was \( p = .182 \)]. Rated mood valence in the Emotion session followed a similar pattern in both session orders: participants’ mood valence stayed stable with neutral video viewing, was reported to decrease after completion of the neutral AX-CPT block, rose again with positive video viewing, and decreased again after completion of the positive AX-CPT block. However, individuals who completed the Emotion session first reported more significant changes in the rated valence of their mood valence between different time intervals of the Emotion session than individuals who completed the Emotion session second (i.e., following the Reward session). In a focused analysis of valence ratings in the Emotion session as a function of time interval, the effect of interval was highly significant for both session orders, but stronger for individuals who completed the Emotion session first \[ F(4,204) = 22.192, p < .001, \eta^2 = .205 \], than for individuals who completed it second \[ F(4,192) = 7.472, p < .001, \eta^2 = .076 \]. This tentatively suggests that, while significant for both groups, the emotion inductions in the Emotion session had a greater effect when participants were engaging in it on their first session visit than when they were returning, having done the Reward session first instead, driving the significant three-way interaction.
Reward session data in both session orders followed a relatively similar pattern to Emotion session data (stable mood valence with first neutral video viewing, decreased mood valence with completion of the baseline AX-CPT block, increased mood valence following the viewing of the second neutral video). Across both session orders, increased mood valence from interval 3 (following AX-CPT block completion) to interval 4 (viewing of the second video) was numerically larger in the Emotion session than in Reward (average increase of 0.97 +/- 0.10, compared to 0.685 +/- 0.12), as should be expected with viewing of a positively-valenced video as opposed to a neutrally-valenced video.

Importantly, when we examined valence ratings specifically from interval 3 to 4 as a function of session (in a separate 2 x 2 ANOVA with interval and session as within-subject factors), we observed a significant interaction of interval x session \( [F(1,96) = 5.133, p = .026] \); while mood valence increased from interval 3 to 4 (i.e., with video viewing after the first AX-CPT block) in both sessions, mood valence became significantly more positive for individuals viewing the positive video (in the Emotion session) than for individuals viewing a second neutral video (in the Reward session). The presence of this significant interaction thus supports the idea that the positive video was successful in increasing positive mood.

Valence ratings also differed when examining the interval from 4 to 5 (i.e., before and after performance of the second AX-CPT block) as a function of session. While rated emotional valence decreased in both the Emotion and the Reward session with performance of the task block, the decrease appeared greater in the Emotion session than in the Reward session. A 2 x 2 ANOVA with session (Emotion, Reward) and interval (interval 4, interval 5) as within-subject factors revealed a significant interaction of session x interval \( [F(1,96) = 4.389, p = .039] \), verifying that while SAM valence ratings decreased
over the rating 4 to 5 interval, the decrease was greater in the Emotion session. In other words, participants reported feeling more positive at interval 4 in the Emotion session (after the positive induction video) than in the Reward session (after a neutral video), but returned to similar mood valences in both sessions at interval 5, which meant a greater decrease in self-reported mood valence in the Emotion session than the Reward session.

For arousal, the ANOVA revealed a significant main effect of time [$F(4,380) = 2.652$, $p = .033$] and a significant main effect of order [$F(1,95) = 4.176$, $p = .044$], but no effects of session were significant [$p > .35$ for session main effect and all interactions]. The significant order effect was due to overall higher reported arousal in participants who did the Emotion session followed by Reward session, compared to those who completed the sessions in the opposite order. Within-subjects simple contrasts of arousal data at individual time intervals revealed that the significant effect of time was due to a decrease in arousal from the first assessment interval (i.e., upon experiment start) to second assessment interval (i.e., after viewing a neutral video clip; $p = .010$) and then an increase again from second to third (i.e., after completion of the first block of the AX-CPT; $p = .021$). Compared to changes in reported mood valence, reported mood arousal stayed more stable and changed less with affective manipulations (i.e., we did not observe significant changes in arousal with the presentation of the positive affect block in the Emotion session, or with the presentation of the reward block in the Reward session). The changes in SAM-reported arousal observed with transition from the neutral to the positive block in the Emotion session were smaller than SAM-reported changes in valence. Greater change in self-reported mood valence than arousal has been observed in other self-reported responses to positive mood induction in the laboratory (Bruyneel et al., 2012). Also, the positive images used were high in positive
valence but moderate in arousal (normed average valence: 7.69, normed average arousal: 4.67). The neutral images used were neutral in valence and relatively low in arousal (normed average valence: 4.90, normed average arousal: 2.61), leading to a larger differential in normed average valence between positive and neutral image sets used (difference of 2.79) than the differential in normed average arousal between the image sets (different of 2.06). Less is known about the effect of reward incentives on mood; while some research suggests that incentives may promote positive mood (Meloy, Russo, & Miller, 2006) and more primary appetitive stimuli (such as erotic pictures) may increase physiological arousal (Walter et al., 2008), to our knowledge no previous studies have explicitly investigated self-reported mood valence and arousal under monetary incentive. It is thus unclear whether secondary rewards, such as money, generally lead to increases in arousal; our SAM data suggest that such an increase in arousal did not occur over the course of the reward block in the present dataset.

In general, the SAM self-report data are consistent with the idea that mood valence remained stable with viewing of neutrally valenced videos, that mood valence became mildly positive with viewing of positively valenced videos, and that completing blocks of the AX-CPT were associated with a drop in mood valence regardless of affect/reward manipulations present in the task.

Effects of Emotion Inductions: IAPS Passive Viewing Run

In this run, pupil dilation in response to passive viewing of IAPS images was examined as a function of valence (neutral versus positive) and old/new status (old being images previously presented as part of the AX-CPT run, new being images presented for the
first time in the passive viewing run). There were no overt task performance measures for
the passive viewing run, only pupil activity in response to stimulus presentation. Pupil
timecourses were extracted as a percentage change measure relative to the last 100ms of
grayscale presentation prior to IAPS image onset for each trial and are shown in Figure 4a.
Pupil dilation during the last 250ms of IAPS image presentation (average magnitude of
pupil dilation during timepoints 5750-6000ms; shown in Figure 4b) was examined using
mixed-model analysis. We chose to examine pupil activity as a function of valence at this
epoch because it occurred at the end of the image presentation, when the image had
already been presented for multiple seconds, in order to compare pupil magnitudes at
maximum possible differentiation as a function of valence.

Passive viewing data was available for 89 subjects (3255 usable observations in
total). Because each IAPS image shown had a different average luminosity that could have
influenced pupil diameter, a linear mixed modeling analysis was conducted on single-trial
data, nested within subjects, examining the two factors of interest (valence and old/new)
while statistically controlling for (i.e., first regressing out) variation in the level of
luminosity of the presented image on each trial (and its associated effect on pupil dilation).
Model fitting was conducted using the \texttt{lme} command in the \texttt{nlme} package for R statistical
software (\url{www.r-project.org}), and the \texttt{multcomp} package was used to extract parameter
estimates and significance levels from the final fitted model. Only the final model is
reported here, which included valence, old/new status, and valence x old/new interaction
as regression parameters. Degrees of freedom are thus calculated as 3163 (calculated as
follows: 3255 – 89 – 3 = 3163; 3255 usable observations minus 89 subjects [random
intercepts to estimate for level 2 units, with single trials serving as level 1 in the present analysis] minus 3 [regression parameters] = 3163).

The model revealed a significant effect of old/new status \([F(1,3163) = 22.53, p < .001]\) but no significant effect of valence \([F(1,3163) = 0.481, p = .49]\) or interaction \([F(1,3163) = 1.452, p = .23]\): pupil dilation was greater during viewing of images that had been previously viewed during the AX-CPT blocks than during viewing of novel images, but did not significantly vary with emotional valence. The significant old/new effect, due to the fact that pupil dilation was greater for previously-seen images than for new images, is consistent with previous literature suggesting that pupil dilation is greater when viewing old compared to new items on recognition memory tests (Otero, Weekes, & Hutton, 2011; Vo et al., 2008).

As a focused comparison to follow up on these findings, we ran an additional analysis examining pupil dilation during presentation of the new images only (1800 usable observations), at the same epoch with valence as a factor, controlling for variation in the level of image luminosity. Valence was insignificant in this analysis as well \([F(1,1553) = 0.1622, p = 0.6872]\).
The observed null effect of valence is surprising, given previous reports that pupil dilation is greater when viewing emotionally evocative stimuli compared to neutral stimuli as a result of autonomic arousal (Bradley et al., 2008). Given that pupil dilation during the passive viewing run showed sensitivity to memory effects, it is possible that the null effect of valence may reflect failure of the positive IAPS images to elicit emotion (or at least emotion-related changes in autonomic arousal), as opposed to poor pupil sensitivity to psychological influences. The implications of this apparent failure to replicate Bradley and colleagues’ findings, where changes in pupil dilation acted as an index of emotional arousal in response to viewing emotionally evocative IAPS stimuli, is discussed further in the Discussion section.

It should be further noted that we examined passive viewing activity in individual subjects and identified a subsample for which pupil dilation was greater when viewing
positive images, compared to neutral images, as originally hypothesized (N=35 out of a total of N=89 with passive viewing data; numerically greater, not tested for statistical significance). We examined Emotion AX-CPT task performance and pupil activity in this subsample and compared these effects to performance and pupil activity in the full sample (full sample analyses described below in Results: Task Performance), but generally it did not appear that this subsample showed greater changes in performance or pupil under the positive emotion manipulation. Results of these comparisons are available in the Supplementary Material text and Table S1.

Results: Task Performance

Results from the Reward session, in which cognitive task performance between baseline and reward incentive conditions was compared, will be described first, followed by results from the Emotion session, in which cognitive task performance between neutral and positive emotion conditions was compared. Finally, comparisons between performance in the Reward and Emotion sessions will be examined. Each subsection follows a highly similar structure, where block-based effects, followed by trial-based effects, of the reward/emotion manipulation will be examined.

Reward AX-CPT Results

Global Incentive Effects

The incentive manipulation was successful in globally improving performance, as participants achieved above-criteria (i.e., rewarded) performance on 69.9% of possible
trials (range: 0-94%), versus the expected rate of 30% reward if performance had remained at baseline levels.

**Block-Based Effects**

These analyses compared task performance on trials in the baseline block and non-incentive trials within the reward block. The error rate ANOVA (results shown in Figure 5a) revealed a significant main effect of block \([F(1,99) = 4.806, p = .031]\), a significant main effect of cue \([F(1, 99) = 60.234, p < .001]\), a significant main effect of probe \([F(1,99) = 64.818, p < .001]\), a significant interaction of block x cue \([F(1,99) = 60.444, p < .001]\) a significant interaction of block x probe \([F(1, 99) = 27.762, p < .001]\), a significant interaction of cue x probe \([F(1,99) = 94.356, p < .001]\), and a significant interaction of block x cue x probe \([F(1,99) = 31.780, p < .001]\). Cue and probe effects were due to higher error rates in AY trials than in other trial types, an effect that has been previously observed when examining AX-CPT performance in healthy young adults (Braver et al., 2002; Braver et al., 2001; Braver, Satpute, Rush, Racine, & Barch, 2005). Incentive-related effects were due to a general pattern closely replicating previous observations of AX-CPT performance under incentive, where AY error rates increased while error rates in all other trial types decreased (Chiew & Braver, 2013; Locke & Braver, 2008). This pattern is consistent with a shift toward proactive control, since enhanced preparatory utilization of context cue information should benefit performance in all trial types except for AY trials, where cue-related expectancy must be overcome upon processing the non-target probe in order to successfully make the non-target response. The RT ANOVA (results shown in Figure 5b) revealed a significant main effect of block \([F(1,99) = 123.171, p < .001]\), a significant main
effect of cue \( F(1, 99) = 538.871, p < .001 \), a significant main effect of probe \( F(1, 99) = 829.668, p < .001 \), and a significant interaction of cue x probe \( F(1, 99) = 526.131, p < .001 \).

While RTs were faster overall in the incentive block, our analysis demonstrated that this effect did not interact with trial type (which showed expected slowing in AY trials).

Figure 5. Task performance measures in the Reward session. Trial-related incentive effects (non-incentive vs. incentive trials) and block-related incentive effects (baseline vs. non-incentive): (a) with error rates as a dependent measure; (b) with RTs as a dependent measure.

When examining block-based effects of incentive on proactive control using proactive indices, the paired t-test revealed that proactive indices were higher in the non-incentive trials than in the baseline trials, for both error rates \( t(99) = 3.413, p = .001 \) and for RTs \( t(99) = 4.673, p < .001 \). Analyzing RTs via proactive index revealed an increase in proactive control that analysis of the raw RTs did not.

Trial-Based Effects

These analyses compared task performance on non-incentive and incentive trials within the reward block. The error rate ANOVA (results shown in Figure 5a) revealed a significant main effect of incentive \( F(1, 99) = 18.813, p < .001 \), a significant main effect of
cue \( F(1,99) = 171.773, p < .001 \), a significant main effect of probe \( F(1,99) = 160.113, p < .001 \), a significant interaction of incentive \( \times \) cue \( F(1,99) = 45.749, p < .001 \), a significant interaction of incentive \( \times \) probe \( F(1,99) = 52.687, p < .001 \), a significant interaction of cue \( \times \) probe \( F(1,99) = 172.720, p < .001 \), and a significant interaction of incentive \( \times \) cue \( \times \) probe \( F(1,99) = 42.047, p < .001 \). These significant results are due to a pattern very similar to that observed as a function of block incentive effects, where AY errors increased with incentive \( (p < .001) \) and errors in all other trial types decreased with incentive \( (AX: p < .001; BX: p = .001; BY: p = .040) \), indicating that trial-by-trial incentive effects were associated with an additional shift towards proactive control. The RT ANOVA (results shown in Figure 5b) revealed a significant main effect of incentive \( F(1,99) = 93.942, p < .001 \), a significant main effect of cue \( F(1,99) = 684.028, p < .001 \), a significant main effect of probe \( F(1,99) = 522.369, p < .001 \), and a significant interaction of cue \( \times \) probe \( F(1,99) = 516.906, p < .001 \). These results indicated typical trial-type effects (slower RTs in AY trials than in other trial types) and an overall speeding of RTs with incentive, but no interaction with trial-type.

To examine trial-based changes in proactive control with incentive, we computed and compared proactive indices for non-incentive and incentive trials within the reward block (for both errors and RTs). The proactive index as calculated by error rates increased significantly in incentive trials relative to non-incentive \( [t(99) = 5.339, p < .001] \), but this increase in proactive control was not observed in RTs \( [t(99) = -.490, p = .625] \).

In conclusion, our Reward AX-CPT data closely replicate previous findings (Chiew & Braver, 2013; Locke & Braver, 2008) that reward incentives in the AX-CPT paradigm led to faster RTs in all trials, and lower error rates in all trial types except for AY trials, where
errors increased, and that these effects occurred both on a block-based and on a trial-based level, consistent with block and trial-level increases in proactive control.

Emotion AX-CPT Results

Block-Based Effects

These analyses compared task performance on trials in the neutral block and neutral trials within the positive block. The error rate ANOVA (results shown in Figure 6a) revealed a significant effect of cue \( [F(1,99) = 29.988, p < .001] \), a significant effect of probe \( [F(1,99) = 51.635, p < .001] \), a significant interaction of block x cue \( [F(1,99) = 10.755, p = .001] \), a significant interaction of block x probe \( [F(1,99) = 4.927, p = .029] \), and a significant interaction of cue x probe \( [F(1,99) = 80.321, p < .001] \). These effects were due to a general pattern of elevated AY errors and decreased errors in all other conditions in the positive block relative to neutral (which also led to the trend-level main effect of lower errors in the positive block). This pattern of performance is consistent with a shift toward proactive control, albeit one of a much smaller magnitude than that observed in patterns of error rates under incentive in the Reward session. The RT ANOVA (results shown in Figure 6b) revealed significant main effects of cue \( [F(1,99) = 485.530, p < .001] \), probe \( [F(1,99) = 550.942, p < .001] \), and a significant interaction of cue x probe \( [F(1,99) = 651.708, p < .001] \). These effects were due to elevated AY RTs relative to all other trial types. No significant block-based effects of emotion on RTs in this analysis were observed.

As in analyses with the Reward Session data, proactive indices were calculated and compared for the block-related emotion contrast (i.e., for the Neutral block and for Neutral
trials within the Positive block) with both error rates and RTs. Neither proactive index comparison led to a significant effect, indicating that while in raw analyses error rates appeared to shift weakly towards greater proactive control in the positive emotion block relative to neutral, this effect was not strong enough to support a significant difference in proactive index measures.

Figure 6. Task performance measures in the Emotion session. Trial-related emotion effects (neutral vs. positive trials within the positive block) and block-related incentive effects (neutral vs. neutral trials within the positive block [neutpos]): (A) with error rates as a dependent measure; (B) with RTs as a dependent measure.

**Trial-Based Effects**

These analyses compared task performance on neutral trials and positive trials within the positive block. The error rate ANOVA (results shown in Figure 6a) revealed a significant main effect of cue \([F(1,99) = 46.276, p < .001]\), probe \([F(1,99) = 58.853, p < .001]\), and a significant interaction of cue \(x\) probe \([F(1,99) = 64.302, p < .001]\). These results were due to elevated AY error rates relative to all others, and did not indicate any significant effects of trial-by-trial emotional manipulations on error rates. The RT ANOVA (results shown in Figure 6b) revealed a trend-level main effect of emotion \([F(1,99) = 3.771, p = .055]\), a significant main effect of cue \([F(1,99) = 568.255, p < .001]\), a significant main effect of probe \([F(1,99) = 574.267, p < .001]\), a significant interaction of emotion \(x\) cue \([F(1,99) = 5.175, p = .025]\), and a significant interaction of cue \(x\) probe \([F(1,99) = 574.268, p\)
These results were due to elevated RTs in AY trials and decreased RTs in all other trial types under positive emotion relative to neutral, which follows the pattern associated with a shift towards greater proactive control, albeit a small one (< 10ms for all four trial types).

When trial-based emotion effects were examined using proactive indices (calculated and compared for neutral trials within the positive block and positive trials), positive trials were found to have a significantly greater proactive index (calculated in RTs) than neutral trials $[t(99) = 2.528, p = .013]$. This indicates that while the shift to proactive control with trial-based positive emotion was numerically small, the difference in proactive indices reached statistical significance.

Relative to reward, our data showed weaker and more inconsistent effects of positive emotion on AX-CPT performance. However, the observed changes in error rates in the block-based analysis and changes in RTs in the trial-based analysis showed worsening of AY performance and enhancement of performance in other trial types with positive emotion relative to neutral, consistent with increased proactive control.

*Emotion versus Reward AX-CPT*

**Block-Based Effects**

To compare between block-based effects on task performance as a function of positive emotion context and reward context, we conducted a 2 x 2 ANOVA with session (emotion, reward) and block condition (i.e., baseline vs. non-incentive within reward block,
or neutral vs. neutral within the positive emotion block) as within-subject factors. This ANOVA was conducted on proactive indices calculated with both error rates and RTs.

With proactive indices calculated using error rates, the ANOVA revealed a significant main effect of block [$F(1,99) = 17.008, p < .001$] and a significant interaction of session x block [$F(1,99) = 4.421, p = .038$]. While proactive indices increased from the first to the second block in both sessions, driving the main effect of block, the increase in proactive control was much larger in the Reward session than in the Emotion session, driving the session x block interaction. When directly contrasted using paired t-tests, proactive indices in the baseline and neutral blocks did not significantly differ from one another [$t(99) = -.294, p = .769$] and the increase in proactive index with block in the Emotion session did not reach significance [$t(99) = -1.465, p = .146$], while directly testing the block effect in the Reward session showed a highly significant effect [$t(99) = 4.673, p < .001$]. These effects are shown in Figure 7.

Figure 7. Proactive indices calculated from error rates for the block-based contrast in Emotion and Reward sessions (Baseline block and Non-Incentive conditions in the Reward session, and Neutral block and Neutral trials within the Positive block [Neutpos] conditions in the Emotion session).
With proactive indices calculated using RTs, the ANOVA revealed a significant main effect of session \([F(1,99) = 4.510, p = .036]\), a trend-level effect of block \([F(1,99) = 3.787, p = .055]\), and a significant interaction of session \(x\) block \([F(1,99) = 10.248, p = .002]\). The main effect of session was due to higher proactive indices overall in the Reward session than in the Emotion session, and the main effect of block was due to higher proactive indices in the second block, compared to the first, but both of these effects were driven by the large increase in proactive control from Baseline to Reward block in the Reward session, leading to the highly significant session \(x\) block interaction. Again, paired \(t\)-tests showed that proactive indices in the baseline and neutral blocks did not significantly differ \([t(99) = -.365, p = .716]\) and the block effect in the Emotion session was not significant when examined alone \([t(99) = .568, p = .571]\), while in the Reward session this contrast was highly significant \([t(99) = -3.413, p = .001]\). The proactive index measures leading to this significant interaction are shown in Figure 8.

Figure 8. Proactive indices calculated from RT for the block-based contrast in Emotion and Reward sessions (Baseline block and Non-Incentive conditions in the Reward session, and Neutral block and Neutral trials within the Positive block [Neutpos] conditions in the Emotion session).
Trial-Based Effects

To compare between block-based effects on task performance as a function of positive emotion context and reward context, we conducted a 2 x 2 ANOVA with session (emotion, reward) and trial condition (i.e., incentive vs. non-incentive within reward block, or neutral within the positive emotion block vs. positive) as within-subject factors. This ANOVA was conducted on proactive indices calculated with both error rates and RTs.

With proactive indices calculated using error rates, the ANOVA revealed a significant main effect of session \( [F(1,99) = 51.118, p < .001] \), a significant main effect of trial \( [F(1,99) = 7.335, p = .008] \), and a significant interaction of session x trial \( [F(1,99) = 25.257, p < .001] \). These effects were due to higher proactive indices in the Reward session than in the Emotion session and in incentive/positive trials compared to non-incentive/neutral trials, but were driven specifically by the increase in proactive index from non-incentive to incentive trials in the Reward session (hence the significant session x trial interaction). Directly comparing proactive indices in the Baseline and Neutral blocks suggested that performance did not significantly differ between them \( [t(99) = -.294, p = .769] \). These effects are shown in Figure 9.

Figure 9. Proactive indices calculated from error rates for the trial-based contrast in Emotion and Reward sessions (Non-Incentive and Incentive conditions in the Reward session, and Neutral trials within the Positive block [Neutpos] and Positive trial conditions in the Emotion session).
With proactive indices calculated using RTs the ANOVA did not reveal any significant effects or interactions involving session or trial. When tested directly, proactive index (in RTs) was significantly higher in positive trials than in neutral trials within the positive block \[ t(99) = 2.528, p = .013 \], but in the same contrast the proactive index (in RTs) did not significantly differ between non-incentive and incentive trials in the Reward session \[ t(99) = -.490, p = .625 \], driving null findings in the combined ANOVA. These proactive indices are shown in Figure 10.

**Figure 10.** Proactive indices calculated from RTs for the trial-based contrast in Emotion and Reward sessions (Non-Incentive and Incentive conditions in the Reward session, and Neutral trials within the Positive block [Neutpos] and Positive trial conditions in the Emotion session).

In summary, task performance results clearly demonstrate a pattern consistent with a robust shift towards proactive control as a result of incentive in the Reward session. This shift was apparent on both a trial-based and a block-based level and was reflected in analyses of proactive index measures. Effects on task performance in the Emotion session were much weaker and did not support the hypothesis that reactive control would increase under positive emotion. Instead, influences of positive emotion appeared to be associated
with a shift towards proactive control. However, analyses of proactive indices indicated that, for the most part, the shift towards proactive control with positive emotion was too small for contrasts to reach significance.

**Results: Pupillometry Measures During AX-CPT Performance**

Pupillometry results will be described following a structure similar to that used previously for *Results: Task Performance*. Results from the Reward session will be described first, followed by results from the Emotion session and comparisons of pupil activity between the Reward and Emotion sessions. As when examining task performance, both block-based effects and trial-based effects of the reward/emotion manipulation on pupil activity will be examined.

**Reward AX-CPT**

**Block-Based Effects**

We conducted a paired *t*-test to compare pupil dilation in the pretrial period (-200 to 0ms) between baseline and reward blocks. Pupil diameter was significantly greater in the reward block than in the baseline block [*t*(88) = 4.102, *p* < .001; shown in Figure 11b and full timecourses for AX trials\(^4\) shown in Figure 11a]. This replicates previous

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\(^4\) Analysis of pretrial data was conducted on all trial data, but we chose to graph only AX trials in this analysis and in the corresponding analysis of Emotion AX-CPT data to show the block-based difference in pupil activity remained consistent over time, in the majority of the trials, as simply as possible (i.e., without graphing timecourses for all four trial types, or averaging the timecourses of the four trial types together, given that pupil activity differed by trial type).
observations of incentive context effects on pupil, which were interpreted as possibly reflecting increased mental effort and/or arousal under incentive (Chiew & Braver, 2013).

Figure 11. (a) Pupil timecourses as a function of incentive status for the sustained incentive contrast in the Reward session (baseline vs. non-incentive AX trials). (b) Sustained incentive effects (as averaged pupil magnitudes) at pretrial period (-200-0ms).

Trial-Based Effects

To examine trial-evoked incentive effects, we compared incentive and non-incentive trial pupil activity within the reward task block at a 250ms period during cue maintenance, prior to probe onset (2550-2800ms; average pupil magnitude within this period shown in Figure 12b; full timecourse shown in Figure 12a). Within this period, the ANOVA revealed a significant main effect of incentive [$F(1,88) = 25.159, p < .001$], due to greater dilation in incentive than non-incentive trials. Additionally, we observed a significant main effect of cue [$F(1,88) = 19.955, p < .001$], and a significant interaction of incentive x cue [$F(1,88) =$
7.568, \( p = .007 \). These cue-related effects reflected greater dilation on B-cue compared to A-cue trials, especially in the incentive trials. This pattern replicates previous results (Chiew & Braver, 2013) and supports the notion that, with pupil dilation as a putative marker of mental effort, greater effort may be exerted with incentive and in B-cue trials relative to A-cue trials. This B > A pattern is intriguing, because it suggests that greater preparatory effort is exerted in non-target trials relative to target trials, possibly due to the utility of the contextual cue, which on B-cue trials indicates the need to overcome the dominant target response bias (i.e., target targets are made on 70% of all trials, and on 87.5% of A-cue trials, but 0% of B-cue trials).

Figure 12. (a) Pupil trial timecourses as a function of incentive status and trial for the incentive cue contrast in the Reward session; (b) Incentive trial effects (as averaged pupil magnitudes) at cue maintenance period (2550-2800ms).
Emotion AX-CPT

Block-Based Effects

A paired-samples t-test was conducted on the pretrial time window (-200 to 0ms) to examine the effect of block (neutral, positive) on pupil dilation. The effect of block was significant \( t(91) = 3.242, p = .002 \) with greater pupil diameter observed in the positive block than in the neutral block (shown in Figure 13b and full timecourses for AX trials shown in Figure 13a). This effect was very similar to the effect observed in the Reward session (greater pupil diameter in reward vs. baseline block). The effect size was larger in the Reward session (\( \eta^2 = .405 \)) than in the Emotion session (\( \eta^2 = .236 \)), but both effects can be classified as large in size (J. Cohen, 1988). However, overt task performance in the neutral versus positive emotion was less differentiated than that between baseline and reward. Given changes in pupil dilation have been attributed to changes in mental effort and/or arousal in the literature, it seems possible that the block-related increase in pupil dilation under reward could be attributed to changes in mental effort; in contrast, given the presence of smaller behavioural effects, the pupil effect in the Emotion session seems less likely to be related to changes in mental effort. Instead, this effect could reflect increased arousal in the positive emotion context relative to neutral emotion. Another alternate interpretation is that this effect reflects time-on-task or order effects, since the positive block always followed the neutral block (similar to the Reward session, where the reward block always followed the baseline block). This alternative explanation will be examined further below in the Time on Task Effects section.
Figure 13. (a) Pupil timecourses as a function of emotion status for the sustained emotion contrast in the Emotion session (neutral vs. neutral AX trials within the positive block). (b) Sustained emotion effects (as averaged pupil magnitudes) at pretrial period (-200-0ms).

**Trial-Based Effects**

To examine trial-evoked emotion effects, we compared positive and neutral trial pupil activity within the positive task block at a 250 ms time window, during cue maintenance prior to probe onset (2550-2800ms; average pupil magnitude within this period shown in Figure 14b; full timecourse shown in Figure 14a). Within this period, the ANOVA revealed a significant main effect of cue \( F(1,91) = 7.526, p = .007 \), due to greater pupil dilation in the B-cue trials than in the A-cue trials. The B > A trial-type effect is similar to those observed in the reward block, suggesting that participants exerted greater cognitive effort on B-cue than A-cue trials once again. However, no significant effects of emotion manipulations on transient pupil activity were observed.
Figure 14. (a) Pupil trial timecourses as a function of emotion status and trial type for the incentive cue contrast in the Reward session; (b) Emotion trial effects (as averaged pupil magnitudes) at cue maintenance period (2550-2800ms).

*Emotion versus Reward AX-CPT*

**Block-Based Effects**

To compare between emotion and reward sessions and blocks on block-related pupil dilation, we conducted a 2 x 2 ANOVA with session (emotion, reward) and block (first and second; i.e., baseline vs. reward, or neutral vs. positive) as within-subject factors on pretrial pupil magnitudes. This ANOVA revealed a significant main effect of session \[F(1,79) = 7.344, p = .008\] due to greater pupil dilation in the Reward session than in the Emotion session, and a significant main effect of block \[F(1,79) = 31.463, p < .001\] due to greater pupil dilation in the affective block (positive/reward versus neutral/baseline), but no significant interaction of session x block \[F(1,71) < 1\]. When analyzed directly against one another, pretrial pupil magnitude in the baseline block of the Reward session was
significantly greater than in the neutral block of the Emotion session \( [F(1,79) = 2.378, p = .02] \). This effect did not interact with session order. This suggests that, when analyzed together, pupil dilation in positive and reward blocks was higher than in neutral and baseline blocks, and that overall tonic pupil activity was elevated in the Reward session blocks compared to Emotion session blocks. The pretrial pupil activity measures used in this analysis are shown in Figure 15.

Figure 15. Pretrial pupil activity (averaged magnitude of -200-0 ms period, during ITI before trial start) for the Baseline and Reward blocks within the Reward session, and the Neutral and Positive blocks within the Emotion session.

Trial-Based Effects

We were also interested in trial-by-trial pupil activity at the cue maintenance period and examining how it differed as a function of emotion/reward sessions and conditions. We conducted a 2 x 2 x 2 ANOVA with session (emotion, reward), trial (i.e., non-incentive vs. incentive within reward block, or neutral vs. positive within positive block), and cue (A-cue or B-cue) as within-subject factors. The ANOVA revealed a significant main effect of
session \([F(1,79) = 8.138, p = .006]\), a significant main effect of trial \([F(1,79) = 14.540, p < .001]\), a significant main effect of cue \([F(1,79) = 28.437, p < .001]\), a significant interaction of session x trial \([F(1,79) = 27.945, p < .001]\), and a significant interaction of session x trial x cue \([F(1,81) = 7.475, p = .008]\). The most important effect of these was the three-way interaction of session x trial x cue, driven by the fact that pupil dilation was much higher in incentive B-cue trials than in any other condition. The other significant interactions in the analyses were generally driven by this effect as well. The pupil dilation measures used in this analysis are shown in Figure 16.

Figure 16. Pupil activity at cue maintenance period (averaged magnitude of 2550-2800ms period, during delay between cue and probe) as a function of experiment session (Reward, Emotion), trial (Non-Incentive and Incentive trials within Reward session, Neutral within Positive block and Positive trials within Emotion session), and cue (A-cue, B-cue): when analyzed together, leading to a significant three-way session x trial x cue interaction, as described in the text.

Post-hoc analyses contrasting pupil dilation in non-incentive (within reward block) vs. neutral (within positive block) trials (x cue) did not lead to any significant effects, showing that transient pupil activity in this control trial condition was similar across
sessions, while contrasting pupil dilation in positive vs. reward trials (x cue) revealed a significant effect of session ($p = .002$) and a significant interaction of session x cue ($p = .021$), verifying that significant differences as a result of session were due specifically to performance in incentive B-cue trials.

Transient Pupil Effects as a Function of Session and Block Context

We next conducted an ANOVA examining normalized pupil dilation at the cue maintenance period as a function of session and block context. Specifically, with the session context contrast, we were interested in examining whether normalized pupil dilation in baseline and neutral blocks was comparable across sessions (i.e., did not significantly differ in magnitude). With the block context contrast, we examined whether normalized pupil dilation differed across blocks (baseline and reward in the Reward session, and neutral and positive in the Emotion session). Examining normalized pupil activity across blocks was of interest, given that preceding analyses utilized non-normalized data taken from the pretrial period to identify sustained (block-based) incentive/emotion effects, and normalized data at the pre-probe period, during cue maintenance, to identify transient (trial-evoked) incentive/emotion effects. Prior evidence suggests that, at least under incentive manipulations, such sustained and transient effects may interact (Chiew and Braver, 2013): under incentive context, where increased sustained pupil activity was observed, decreased normalized (i.e., transient) pupil activity was observed in non-incentive trials, relative to baseline trials. This suggested a shift towards greater sustained activity and decreased transient activity with incentive context. Whether a similar dynamic shift may occur under
positive emotion context, in which the present data also demonstrated increased sustained pupil activity, is at present unclear.

We thus conducted a 2 x 2 ANOVA on normalized pupil dilation at the cue maintenance period (collapsed across trial types, in the baseline, non-incentive within reward block, neutral, and neutral within positive block conditions), with session (emotion, reward) and block (first, second) as within-subject factors. Timecourses are shown in Figure 17a, with averaged pupil magnitudes at the cue maintenance period shown in Figure 17b. The ANOVA revealed a significant main effect of session \([F(1,79) = 7.295, p = .009]\) and block \([F(1,79) = 7.797, p = .007]\), but no significant interaction of session x block \([F(1,79) = .321, p = .573]\).

The session effect was due to higher normalized pupil dilation in the Emotion session than in the Reward session; focused \(t\)-tests verified that this effect was present both in comparing the neutral-within-positive-block trials to non-incentive (within reward block)
trials \((p = .037)\), but also even when comparing neutral block trials to baseline block trials \((p = .044)\). It is unclear why the neutral block and baseline block should differ in trial-evoked transient pupil magnitude, but it is consistent with the finding that tonic pupil activity, as measured by pretrial pupil dilation, was also greater in the baseline block than in the neutral block \((p = .02;\) in pupillometry results for Emotion versus Reward AX-CPT: Block Based Effects). Together, these observations suggest that transient pupil activity is inversely correlated with sustained pupil activity. Specifically, these results, together with previous results from pretrial pupil data, indicate that sustained pupil activity was higher and transient pupil activity was lower in the emotion/motivation blocks (reward/positive) than in the control blocks (baseline/neutral). In the Reward session, this specifically occurred when contrasting baseline block trials to non-incentive trials within the Reward block: on incentive trials within the Reward block, increases in both sustained and transient pupil activity appeared to be present. We did not observe an analogous increase in transient pupil activity when examining positive trials within the Positive block in the Emotion session.

The mechanisms underlying these similar patterns of dynamic change in pupil activity under both incentive and emotion contexts are unclear, given that differing behavioural patterns were observed as a result of these contexts. As previously described in the Task Performance: Emotion versus Reward AX-CPT: Block-Based Effects section, proactive control (measured by proactive indices) significantly increased with block in the Reward session. While proactive indices similarly increased in the Positive block relative to Neutral block in the Emotion session, this increase was smaller and did not reach significance. It is possible that different mechanisms underlie these patterns of pupillary
change, or that changes in pupil dilation with these manipulations do not solely reflect changes in cognitive effort – these possibilities are discussed in more detail in the Discussion section.

*Time on Task Effects: Task Performance and Pupil Activity*

The following analyses examined task performance and pupil activity as they changed over time within task blocks. These analyses were conducted to clarify the extent to which gradual change may have occurred over the course of task blocks as a result of time on task effects (i.e., practice, fatigue, possible mood dissipation) and to help clarify whether changes in performance/pupil observed in the present study as a function of block could be attributed to such effects as opposed to the intended experimental manipulation (reward motivation / positive emotion). We divided each of the four AX-CPT blocks completed by the participant (Baseline and Reward blocks in the Reward session, and Neutral and Positive blocks in the Emotion session) into four 50-trial periods each and examined task performance (error rates and RTs) and pretrial pupil magnitude (in the 200 ms prior to trial start) over the course of these periods. Time on task results are shown in Figures 18-20.

To examine effects on performance and pupil specifically as a result of the block-based contrast, we compared baseline block trials to non-incentive trials within the Reward block, and to neutral block trials within the Emotion block. In the first set of analyses, separate analyses were conducted for the Emotion and Reward sessions. Performance and pupil measures were analyzed within each experimental session, using 2x4 repeated-measures ANOVAs that included task block (first block, second block) and
trial section (first, second, third, fourth) as within-subjects factors. Separate analyses were conducted for the Emotion and Reward sessions.

In the analyses of the Reward session, using error rates as a dependent measure, a significant main effect of section \(F(3,297) = 11.344, p < .001\) but no significant effect of block \(F(1,99) = .349, p = .556\) or block x section interaction \(F(3,297) = .508, p = .677\). This pattern was due to higher errors in block 3 and 4 than in 1 and 2. The lack of an interaction with block indicates that this pattern was similar in both task blocks.

Figure 18. Task performance as a function of 50-trial sections, with error rates as a dependent measure: (A) in the baseline block and non-incentive trials within the reward block of the Reward session; (B) in the neutral block and neutral trials within the positive block of the Emotion session.
Figure 19. Task performance as a function of 50-trial sections, with RTs as a dependent measure: (A) in the baseline block and non-incentive trials within the reward block of the Reward session; (B) in the neutral block and neutral trials within the positive block of the Emotion session.

Figure 20. Pupil activity during the 200ms pretrial period as a function of 50-trial sections: (A) in the baseline block and non-incentive trials within the reward block of the Reward session; (B) in the neutral block and neutral trials within the positive block of the Emotion session.
With RTs as a dependent measure, the ANOVA revealed a significant main effect of block \( [F(1,99) = 157.575, p < .001] \), with higher RTs in the Baseline block than the Reward block, but no significant effect of section \( [F(1,99) = 1.676, p = .172] \) or block x section interaction \( [F(1,99) = 1.620, p = .185] \). With pupil magnitude as a dependent measure, the Reward session ANOVA revealed significant main effects of both block \( [F(1,84) = 20.847, p < .001; \text{Reward} > \text{Baseline}] \) and section \( [F(3,252) = 6.956, p < .001; \text{due to a decrease in pupil diameter from section 1 to 2, followed by recovery}] \), but no significant block x section interaction \( [F(3,252) = 2.025, p = .111] \). The lack of a block x section interaction in all three dependent measures is important because it suggests that any time-on-task effects (i.e., the section factor) were not different in the Reward block compared to Baseline.

These analyses were repeated to examine data in the Emotion session. With error rates as a dependent measure, the Emotion session ANOVA revealed a significant effect of section \( [F(3,300) = 5.977, p = .001] \), due to increasing errors over the trial sections, but not of block \( [F(1,100) = 1.836, p = .178] \) or block x section interaction \( [F(3,300) = .952, p = .416] \). While this effect could be due to increasing boredom or fatigue within a task block, the lack of a significant block x section interaction suggests errors followed similar patterns in both blocks, and that boredom/fatigue did not “carry over” from one block to the next. With RTs as a dependent measure, the Emotion session ANOVA revealed a significant block x section interaction \( [F(3,300) = 3.274, p = .021] \), but no significant effect of block \( [F(1,100) = .047, p = .828] \) or section \( [F(3,300) = 1.505, p = .213] \). The block x section interaction was due to significant decreases in RTs from section 1 to sections 3 and 4 in the Neutral block, but a differential pattern in the Positive block, with an increase in RTs from section 1 to section 2. This suggests the presence of a practice effect in the Neutral block that was not
present in the Positive block. Yet this effect was not strong enough to drive global
differences between task blocks, given a null effect in RTs in the main block-based emotion
contrast. With pupil magnitude as a dependent measure, the Emotion session ANOVA
revealed a significant main effect of block \(F(1,84) = 9.903, p = .002; \text{Positive > Neutral}\) and
section \(F(3,252) = 4.051, p = .008; \text{decrease in pupil diameter from section 1 to 2, then}
recovery}\), but no significant block x section interaction. \(F(3,252) = .916, p = .433\). Thus, in
general, the Emotion session seemed to follow a similar pattern to the Reward session,
with time-on-task effects being independent of block.

To test the hypothesis that the Reward and Emotion sessions were similar in terms
of time-on-task effects more directly, we added session (Reward, Emotion) as an additional
factor to the ANOVAs. Thus, we ran 2 x 2 x 4 repeated-measures ANOVAs with session,
block, and trial section, as within-subjects factors, on error rates, RTs, and pupil magnitude
at the cue maintenance period as dependent measures. With error rates as a dependent
measure, the ANOVA revealed a significant effect of trial section \(F(3,297) = 12.244, p
< .001\), due to increasing errors over the course of each task block, but no other significant
effects. With RTs as a dependent measure, the ANOVA revealed a significant main effect of
block \(F(1,99) = 107.543, p < .001\), a significant interaction of session x block \(F(1,99) =
102.432, p < .001\), and a significant interaction of session x block x section \(F(3,297) =
3.198, p = .024\). These effects were due primarily to the abrupt decrease in RTs from the
Baseline to Reward block in the Reward session, which was not present in the Emotion
session. The session x block x section interaction reflected that the block x section
interaction was not significant in Reward session data \((p = .185)\), while in the Emotion
session data, the block x section interaction reached significance \((p = .021)\). While RTs sped
up in the reward block relative to baseline, patterns of change in RTs over the course of the block were relatively similar in the baseline and reward block. In the Emotion session data, RT dynamics differed with section between the neutral and positive blocks: the significant interaction is driven by a slowing in RTs in the second section of the positive block that was not present in the neutral block. With pupil magnitude as a dependent measure, the ANOVA revealed significant main effects of session \( F(1,69) = 5.821, p = .019; \) Reward > Emotion, block \( F(1,69) = 28.708, p < .001; \) Reward/Positive > Baseline/Neutral, and section \( F(3,207) = 6.774, p < .001; \) characterized by a decrease in pupil diameter from section 1 to 2, followed by recovery, but no significant interactions. Thus, these results suggest that the Reward and Emotion sessions were similar in time-on-task effects in errors and pupil dilation, but did show some differences in terms of the RT pattern.

Finally, we conducted a series of analyses to focus on the transition period between task blocks: specifically examining performance and pupil activity in the last trial section of the first (i.e., Baseline/Neutral) block, compared to the first trial section of the second (i.e., Reward/Positive) block, as they differed as a function of session. This analysis was intended to specifically examine whether performance/pupil change from the first to the second block was greater (i.e., less gradual) in the Reward session (i.e., from the Baseline block to the Reward block) than in the Emotion session (i.e., from the Neutral to the Positive block). We thus computed a 2 x 2 ANOVA with session (Emotion, Reward) and trial section (last section of first block, first section of second block) as within-subject factors for each dependent measure. With errors as a dependent measure, the ANOVA revealed a significant main effect of trial section \( F(1,99) = 9.015, p = .003 \), but no other significant effects. This effect was due to decreases in the first section of the second task block, relative
to the last section of the first task block, across sessions. With RTs as a dependent measure, the ANOVA revealed a significant main effect of trial section \([F(1,99) = 41.411, p < .001]\) and session \(\times\) block interaction \([F(1,99) = 35.386, p < .001]\). The section effect was due to faster RTs at the beginning of the second task block, relative to the end of the first, but the interaction indicates that this effect was driven by a steep drop in RTs from Baseline to Reward block; directly testing the transition in the Emotion session showed that RTs did not significantly change from the last section of the Neutral block to the first section of the Positive block \((p = .965)\). With pupil magnitude as a dependent measure, the ANOVA revealed a significant main effect of session \([F(1,75) = 6.294, p = .014; \text{Reward} > \text{Emotion}]\) and block \([F(1,75) = 9.844, p = .002; \text{Reward}/\text{Positive} > \text{Baseline}/\text{Neutral}]\) but no significant interaction.

This profile of pupil activity is similar to that observed in Chiew and Braver (2013). RT effects in the Reward session were also highly similar to those previously observed. Error effects were somewhat different from those observed in Chiew and Braver (2013); while in that dataset error rates stayed relatively stable over the four 50-trial sections in each task block, in the present dataset we observed increases in error rates over time in all task blocks, regardless of emotional/motivational manipulation. The experimental protocol in the present study was longer and more complex than that used by Chiew and Braver (2013), and fatigue may thus have occurred to a greater extent and had a greater influence on performance than in that previous study. However, possible fatigue effects appeared to be relatively limited to occurring within task block, rather than extending to the subsequent task block. While pupil diameter was higher in the Reward session than the Emotion session overall, the lack of a significant session \(\times\) block \(\times\) section interaction when
pupil diameter was examined suggests that the pattern of pupil dynamics over the course of task blocks did not significantly differ with reward versus emotion. Overall, changes in performance and pupil activity as a function of trial section within each task block appeared consistent with interpretations that block-based effects were due to experimental manipulations of emotion and reward, as opposed to practice or fatigue-related effects, although increases in error rates suggested that fatigue could be leading to decrements in performance within task blocks.

**Pupil-Behaviour Correlations**

As a follow-up to analyses examining the effects of experimental manipulations on cognitive control performance and related pupil activity, we examined correlations directly between task performance measures and pupil activity to clarify whether pupil activity, as a putative measure of cognitive effort, could be directly related to overt behaviour, and whether this relationship changed under reward conditions.

We specifically tested the hypothesis that pupil activity at the cue maintenance period (2550-2800ms, just prior to probe onset) and at the pretrial period (-200-0ms, ITI just prior to trial onset) would positively correlate with proactive control. A second hypothesis tested in the data was that pupil activity at these periods would positively correlate with faster RTs more generally (evidence that pupil dilation may relate to faster RTs, but not specifically to enhanced cognitive control, was recently observed by Van Steenbergen and Band in a conflict task; (van Steenbergen & Band, 2013). A third hypothesis tested in this data was that these relationships might strengthen under incentive. The first hypothesis was established on the basis of literature suggesting that
pupil dilation is a putative measure of effort (e.g., (Beatty, 1982b), but we hypothesized that the pupil-behaviour relationship may strengthen with incentive given observations demonstrating that the pupil is sensitive to incentive influences, even when overt performance (i.e., RTs) is matched between incentive and non-incentive trials (Chiew & Braver, 2013).

We chose to focus on correlations relating to these relationships specifically within Reward session data and did not examine pupil-behaviour correlations in the Emotion session data to conserve power, given that task performance under reward incentive in the present study was more characteristic of increased mental effort than task performance under positive emotion, changes in pupil activity in response to reward were more robust and consistent, and evidence from our previous dataset suggested that the pupillary response may be related both to task performance and to incentive status.

To measure the relationship between pupil dilation and proactive control, we used the proactive index as a behavioural measure of proactive control (as described in the Task Performance Results), calculated using both errors and RTs, in the incentive and non-incentive conditions within the reward block. Further, we used these indices to calculate a difference score, Incentive—Non-Incentive (i.e., the extent to which proactive control increased under incentive relative to non-incentive trials within the reward block). These measures were correlated with pupil magnitudes at the cue maintenance period (measured, as before, in percentage change from baseline). We also correlated proactive indices with pupil dilation at the pretrial period. Because pupil activity at the pretrial period was calculated in absolute values instead of as a measure of change, analyses relating pupil activity at this period to task performance used measures of change between conditions.
Given that the pretrial pupil effects were block-related in nature, we calculated block contrasts in performance and pupil activity to correlate. Thus, we calculated a difference score of Non-Incentive—Baseline proactive indices (i.e., the extent to which proactive control increased under non-incentive trials in the reward block relative to baseline block trials) to correlate with Non-Incentive—Baseline pretrial pupil activity. We also conducted regression analyses between Baseline and Non-Incentive performance (proactive indices) and pretrial pupil activity and calculated the residuals for each regression (i.e., variance in Non-Incentive performance/pupil after controlling for Baseline) and examined the relationship between the residuals using correlation. Because of the sensitivity of the correlation analyses to outliers, outliers in the distributions were identified using the extreme studentized deviate (ESD) method (Grubbs, 1969) and eliminated from the data.

Of the correlations examining the relationship between proactive control (as measured by performance-based proactive indices) and pupil dilation at the cue maintenance period, we observed a significant positive correlation between the Baseline proactive index (calculated in RTs) and Baseline B-cue pupil dilation \( r(98) = .208, p = .04 \) and between Non-Incentive proactive index (calculated in error rates) and Non-Incentive B-cue pupil dilation \( r(99) = .227, p = .024 \). However, Incentive proactive indices (calculated from both error rates and RTs) and Incentive B-cue pupil dilation did not significantly correlate (error proactive index: \( r(99) = .140, p = .163 \); RT proactive index: \( r(99) = .108, p = .287 \)). Also, a trend-level positive correlation was observed between Incentive—Non-Incentive proactive index (calculated in error rates) and Incentive—Non-Incentive B-cue pupil dilation \( r(99) = .174, p = .085 \). Scatterplots of these significant and trend-level relationships are shown in Figure 21. These findings provide support that pupil
dilation at the cue maintenance period may reflect proactive control, including evidence, albeit at a trend level, that incentive-related increases in pupil dilation may predict incentive-related increases in proactive control. However, it should be noted that when corrected for multiple comparisons using the false discovery rate procedure (Benjamini & Hochberg, 1995) these significant correlations did not survive correction (all corrected p-values = .36 or higher), so these should be taken as exploratory analyses.

Figure 21. Scatterplots showing significant and trend-level relationships between task performance proactive indices and pupil dilation at cue maintenance period in the Reward session. (a) Baseline block proactive index (from RTs) plotted against pupil dilation at cue maintenance in Baseline B-cues (p = .04); (b) Non-incentive proactive index (from errors) plotted against pupil dilation at cue maintenance in Non-Incentive B-cues (p = .024); (c) Incentive—Non-Incentive proactive index (from errors) plotted against pupil dilation at cue maintenance in Incentive—Non-Incentive B-cues (p = .085).

Of the correlations examining the relationship between proactive control (as measured again by proactive indices) and pupil activity at the pretrial period, in terms of relative change measures with incentive context, no significant correlation was observed between proactive index difference scores (Non-Incentive—Baseline) and pretrial pupil difference scores (Reward—Baseline), for proactive indices calculated with either error rates or RTs. When correlation analysis was conducted on residuals of the regressions of
Baseline—Non-Incentive proactive indices and Baseline—Reward pretrial activity (i.e., on Non-Incentive condition related variance, controlling for Baseline), no significant effect was observed. These null findings suggest that no significant relationship could be observed between changes in proactive control and changes in tonic pupil activity (i.e., observed at the pretrial period) as a function of incentive context.

Following the correlations between pupil and task performance using an index of proactive control, we conducted a second set of correlations to measure relationships between averaged pupil magnitudes at the same time periods (cue maintenance and pretrial) and median correct RTs in the same conditions. No significant effects were observed between RTs and pupil dilation in any of these correlations.

**Results: Individual Difference Measures**

We were interested in investigating relationships between individual difference measures and task performance/pupillometry measures in the hopes of helping clarify the mechanisms by which cognitive control and related pupillary activity may be employed, and how emotion and reward incentive manipulations may influence these processes. Specifically, we were interested in testing the following hypotheses:

(1) *Higher reward sensitivity (indexed by GRAPES-REW, BAS, and RFQ-Promotion) is positively correlated with increased proactive control and increased preparatory pupil dilation under incentive.*

(2) *Higher induced positive emotion (indexed by SAM assessments) is positively correlated with positive affect/reward-related stable individual differences and decreased proactive control in the positive emotion task block, compared to neutral.*
(3) Working memory capacity (indexed by the O-Span) is positively correlated with proactive control and tonic pupil activity in baseline / neutral task blocks.

(4) Trait anxiety (indexed by the STAI) is negatively correlated with proactive control in baseline / neutral task blocks.

It should be noted that Hypothesis 2, regarding the effects of positive emotion on cognitive control, was more tentative given the presence of mixed evidence regarding its effect. Also, while most of these hypotheses included predictions regarding pupil activity, these predictions are more exploratory than the predictions involving task performance data, given that pupil data may be noisier than performance data, and evidence regarding its relationship with individual differences and their influence on cognition is relatively sparse. We were interested in conducting these correlations on an exploratory basis to examine whether individual differences could be used to enhance interpretation of pupil activity collected in conjunction with cognitive performance.

Data for stable individual difference measures was examined for outliers using the extreme studentized deviate (ESD) method (Grubbs, 1969) and eliminated from all subsequent analysis. Likewise, outliers were removed from the task performance and pupil measures as described in the Pupil-Behaviour Correlations section. Because SAM ratings were reported on a 5-point Likert scale instead of a more continuous distribution, no outliers were removed from the SAM data. Outliers eliminated will be specified in each analysis below.

Means and standard deviations for stable individual differences in our participant sample, along with published norms (where available), are listed in Table 2. Given the transient nature of the SAM assessments, they were not included in this table.
Table 2. Means and standard deviations (listed in brackets) for stable individual differences in the present sample, compared to published norms for the corresponding population (healthy young adults; where available).

<table>
<thead>
<tr>
<th>Individual Difference Measure</th>
<th>Present Sample</th>
<th>Published Norms $^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>BAS-Drive</td>
<td>9.50 (2.43)</td>
<td>10.52 (1.93)</td>
</tr>
<tr>
<td>BAS-Fun Seeking</td>
<td>10.29 (3.01)</td>
<td>10.79 (2.92)</td>
</tr>
<tr>
<td>BAS-Reward Responsivity</td>
<td>11.94 (4.96)</td>
<td>15.56 (5.11)</td>
</tr>
<tr>
<td>BIS</td>
<td>17.22 (2.83)</td>
<td>20.19 (4.12)</td>
</tr>
<tr>
<td>NEO-FFI Neuroticism</td>
<td>32.94 (10.17)</td>
<td>34.32 (7.27)</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
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</tr>
<tr>
<td>NEO-FFI Extraversion</td>
<td>39.44 (6.48)</td>
<td>41.16 (6.04)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEO-FFI Openness</td>
<td>35.96 (4.96)</td>
<td>35.25 (6.11)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEO-FFI Agreeableness</td>
<td>43.14 (7.10)</td>
<td>47.68 (10.29)</td>
</tr>
<tr>
<td></td>
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<tr>
<td>NEO-FFI Conscientiousness</td>
<td>41.00 (5.93)</td>
<td>44.41 (5.86)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PANAS-Positive</td>
<td>28.30 (6.68)</td>
<td>27.32 (6.58)</td>
</tr>
<tr>
<td>PANAS-Negative</td>
<td>15.48 (5.99)</td>
<td>14.55 (5.08)</td>
</tr>
<tr>
<td>RFQ-Promotion</td>
<td>21.65 (3.64)</td>
<td>21.64 (3.47)</td>
</tr>
<tr>
<td>RFQ-Prevention</td>
<td>16.82 (3.76)</td>
<td>18.98 (3.91)</td>
</tr>
<tr>
<td>GRAPES-Reward</td>
<td>7.68 (2.64)</td>
<td>6.94 (2.67)</td>
</tr>
<tr>
<td>GRAPES-Punishment</td>
<td>7.22 (2.64)</td>
<td>8.04 (3.24)</td>
</tr>
<tr>
<td>O-SPAN Total</td>
<td>65.58 (7.54)</td>
<td>61.20 (13.30)</td>
</tr>
<tr>
<td>STAI-Trait Anxiety</td>
<td>43.07 (11.30)</td>
<td>40.52 (9.32)</td>
</tr>
</tbody>
</table>

Hypothesis 1 Analyses: Reward Sensitivity and Proactive Control

To address Hypothesis 1, we examined relationships between reward sensitivity and task performance/pupil activity using composite measures calculated both via averaging of measures of interest and factor analysis. In these analyses we tested hypotheses regarding the relationship between reward sensitivity and performance/pupil activity under incentive. Exploratory analyses investigating relationships between punishment-

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$^5$ Norms obtained from the following publications, cited in References: Jorm et al., 1999 (BIS/BAS), McCrae & Costa, 2004 (NEO-FFI), Watson et al., 1988 (PANAS), Redick et al., 2012 (O-SPAN), Spielberger, 1985 (STAI). McCrae & Costa presented two normative samples for NEO-FFI data: Norm 1 was obtained from high-school students (ages 14-18) and Norm 2 was obtained from adults ages 19-93. Given that the present study sample consists of young adults ages 18-30 (mean age 21.0 years +/- 0.27), it seemed reasonable to present both norms.
related measures and behaviour, and between both reward/punishment-related measures and behaviour under positive emotion manipulation, were also conducted and are available in the Supplementary Material. Task performance and pupil variables correlated with individual difference composite measures are listed in Table 3.

Table 3. Task performance and pupil activity variables correlated with stable personality measures related to reward and punishment processing (compiled as average composites and via factor analysis).

<table>
<thead>
<tr>
<th>Task Performance Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reward Rates</td>
</tr>
<tr>
<td>Global Errors – Positive Block</td>
</tr>
<tr>
<td>Global Errors – Reward Block</td>
</tr>
<tr>
<td>Global RTs – Positive Block</td>
</tr>
<tr>
<td>Global RTs – Reward Block</td>
</tr>
<tr>
<td>Proactive Index – Neutral Block Trials, Neutral Trials in Positive Block, Positive Trials (for errors and RTs)</td>
</tr>
<tr>
<td>Proactive Index – Baseline Block Trials, Non-Incentive Trials in Reward Block, Incentive Trials in Reward Block (for errors and RTs)</td>
</tr>
<tr>
<td>Incentive—Non-Incentive Proactive Index (difference score; for errors and RTs)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pupil Activity Measures (unless otherwise stated, used average magnitude at cue maintenance period, 2550-2800ms, extracted as %change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incentive A-cue</td>
</tr>
<tr>
<td>Incentive B-cue</td>
</tr>
<tr>
<td>Non-Incentive A-Cue</td>
</tr>
<tr>
<td>Non-Incentive B-Cue</td>
</tr>
<tr>
<td>Incentive—Non-Incentive A-Cue</td>
</tr>
<tr>
<td>Incentive—Non-Incentive B-Cue</td>
</tr>
<tr>
<td>Neutral in Positive Block A-Cue</td>
</tr>
<tr>
<td>Neutral in Positive Block B-Cue</td>
</tr>
<tr>
<td>Positive A-Cue</td>
</tr>
<tr>
<td>Positive B-Cue</td>
</tr>
<tr>
<td>Reward—Baseline (Pretrial period, -200-0ms, in raw units)</td>
</tr>
</tbody>
</table>

We conducted a set of initial analyses using averaged reward and punishment composite measures calculated as follows: three measures of reward sensitivity (BAS, GRAPES-REW, and RFQ-promotion) and three measures of punishment sensitivity (BIS, GRAPES-PUN, and RFQ-prevention) were collected, z-normalized, and used to create two composite measures: one for reward sensitivity (BAS, GRAPES-REW and RFQ-promotion, averaged together) and one for punishment sensitivity (BIS, GRAPES-PUN, and RFQ-
These measures were created to follow prior related studies that had used these composite measures to detect individual differences effects of reward motivation with different tasks and measures of cognitive control (Jimura et al., 2010; Savine, Beck, Edwards, Chiew, & Braver, 2010). Results of correlations with the composite reward sensitivity measure are examined in the present section; results with the composite punishment sensitivity measure are discussed in the Supplementary Material. 99 subjects (of N=100 total) had the BAS, GRAPES and RFQ data needed to calculate these composite measures. No outliers were eliminated from this analysis.

The composite reward sensitivity measure did not correlate significantly with reward rate \[ r(98) = -0.030, p = .769 \]. Also, when this reward sensitivity measure was correlated with raw error and RT measures in the reward block, no significant correlations were observed.

Next, we correlated the composite reward sensitivity measure with performance calculations of the proactive index, a standardized score calculated on RTs and error rates that measures the relative tendency towards proactive control (as previously described in Results: Task Performance). Hypothesis 1 predicted that reward sensitivity would be positively correlated with increasing proactive index measures under incentive. However, correlation of the reward sensitivity measure with proactive indices was insignificant in incentive and non-incentive conditions as well as the difference between them (Incentive—Non-Incentive), for both error rates and RTs. Analysis results are shown in Table 4.

In order to examine the relationship between reward sensitivity and changes in pupil activity, we correlated the reward sensitivity measure with averaged pupil dilation during the same 250ms period of cue maintenance previously used to examine trial-evoked
effects of incentive/affect manipulations (2550-2800ms), as a function of incentive and cue (A, B), in the Reward block. No significant effects between Reward Sensitivity and pupil activity under incentive at cue maintenance or the pretrial period were observed (all $p$-values > .30). Analysis results are shown in Table 4.

Surprisingly, the reward sensitivity measure appeared to be correlated with pupil activity at cue maintenance in non-incentive A-cue trials, but not incentive A-cue trials; this pattern was not consistent with our hypothesis that reward sensitivity would be more closely related to pupil dilation in incentive, versus non-incentive, trials. Reward sensitivity also negatively correlated with Incentive—Non-Incentive pupil activity for both A-cue and B-cue trials, which ran opposite to predictions: the more highly reward sensitive an individual was, the smaller the preparatory pupil activity increase under incentive, relative to non-incentive, trials. This effect appears to be driven by significant correlations between reward sensitivity and pupil activity in non-incentive trials, rather than incentive trials.
Table 4. Results of correlation analyses between the Reward Sensitivity composite measure and key measures of performance and pupil activity under incentive.

<table>
<thead>
<tr>
<th>Measures Correlated with Reward Sensitivity (composite measure)</th>
<th>Analysis Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reward Rates</td>
<td>$r(98) = -.030, p = .769$</td>
</tr>
<tr>
<td>Raw error rates in Reward block</td>
<td>$r(98) = .054, p = .596$</td>
</tr>
<tr>
<td>Raw RTs in Reward block</td>
<td>$r(98) = .017, p = .870$</td>
</tr>
<tr>
<td>Non-Incentive Proactive Index (error rates)</td>
<td>$r(98) = -.029, p = .774$</td>
</tr>
<tr>
<td>Non-Incentive Proactive Index (RTs)</td>
<td>$r(98) = -.002, p = .986$</td>
</tr>
<tr>
<td>Incentive Proactive Index (error rates)</td>
<td>$r(98) = .060, p = .559$</td>
</tr>
<tr>
<td>Incentive Proactive Index (RTs)</td>
<td>$r(98) = -.034, p = .737$</td>
</tr>
<tr>
<td>Incentive-Non-Incentive Proactive Index (error rates)</td>
<td>$r(98) = .067, p = .514$</td>
</tr>
<tr>
<td>Incentive-Non-Incentive Proactive Index (RTs)</td>
<td>$r(98) = -.166, p = .109$</td>
</tr>
<tr>
<td>Non-Incentive pupil activity at cue maintenance (A-cue)</td>
<td>$r(98) = .312, p = .002$</td>
</tr>
<tr>
<td>Non-Incentive pupil activity at cue maintenance (B-cue)</td>
<td>$r(98) = .198, p = .052$</td>
</tr>
<tr>
<td>Incentive pupil activity at cue maintenance (A-cue)</td>
<td>$r(98) = -.034, p = .741$</td>
</tr>
<tr>
<td>Incentive pupil activity at cue maintenance (B-cue)</td>
<td>$r(98) = -.098, p = .338$</td>
</tr>
<tr>
<td>Incentive—Non-Incentive pupil activity at cue maintenance (A-cue)</td>
<td>$r(98) = -.282, p = .005$</td>
</tr>
<tr>
<td>Incentive—Non-Incentive pupil activity at cue maintenance (B-cue)</td>
<td>$r(98) = -.199, p = .049$</td>
</tr>
<tr>
<td>Pretrial pupil activity in Reward block</td>
<td>$r(94) = -.061, p = .560$</td>
</tr>
<tr>
<td>Pretrial pupil activity in Baseline block</td>
<td>$r(94) = -.170, p = .104$</td>
</tr>
<tr>
<td>Reward—Baseline pupil activity</td>
<td>$r(94) = .168, p = .106$</td>
</tr>
</tbody>
</table>

**Reward Sensitivity and Proactive Control: Developing a Reward Sensitivity Measure via Factor Analysis**

Following up on these initial analyses using composite measures of reward/punishment sensitivity, we conducted factor analysis on several of our individual difference measures related to emotion and reward/punishment processing to develop more nuanced composite measures with which to examine relationships between stable individual differences and performance/pupil activity. 85 participants had complete individual difference data to use in factor analysis and subsequent correlation analyses.
We had several individual difference measures that were anticipated to share common variance as indices of positive affect/reward sensitivity and negative affect/punishment sensitivity measures. The measures that have been considered indices of positive affect and reward sensitivity include: BAS (composite of the three BAS subscales: Drive, Fun Seeking, and Reward Responsivity), PANAS-Positive Affect subscale, RFQ-Promotion subscale, GRAPES-Reward Expectancy subscale, and the Extraversion factor of the NEO. The measures that have been considered indices of negative affect and punishment sensitivity include BIS, PANAS-Negative Affect subscale, RFQ-Prevention subscale, GRAPES-Punishment Expectancy subscale, and the Neuroticism factor of the NEO. We subjected these ten subscale measures (z-standardized) to a factor analysis (factors with an eigenvalue > 1, Varimax rotation) to test whether a two-factor solution fit the data, with one factor representing common variance among the positive affect/reward sensitivity scales, and one factor representing common variance among the negative affect/punishment sensitivity scales.

The factor analysis revealed a four-component solution, accounting for 70.0% of the variance (results shown in Table 5). The first factor explained 28.6% of the variance, and was positively related to Extraversion, PANAS-Positive Affect, RFQ-Promotion, GRAPES-Reward Expectancy, and RFQ-Prevention, negatively related to Neuroticism and GRAPES-Punishment Expectancy, and not closely related to BAS, PANAS-Negative Affect, or BIS. The second factor explained 18.0% of the variance, was positively related to Extraversion, BAS, and BIS, and not closely related to any other measures. The third factor explained 12.3% of the variance, and was positively related to Neuroticism and PANAS-Negative Affect, negatively related to Extraversion and RFQ-Promotion, and not closely related to PANAS-
Positive Affect, GRAPES-Reward, BAS, RFQ-Prevention, GRAPES-Punishment Expectancy, or BIS. The fourth factor explained 11.1% of the variance, and was positively related to RFQ-Prevention and GRAPES-Punishment, but not closely related to any other measures.

Table 5. Results of factor analysis on personality measures related to reward and punishment processing. Rotated component matrix, four components (eigenvalues > 1). All measures z-scored.

<table>
<thead>
<tr>
<th></th>
<th>Component 1</th>
<th>Component 2</th>
<th>Component 3</th>
<th>Component 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraversion</td>
<td>.569</td>
<td>.535</td>
<td>-.188</td>
<td>-.150</td>
</tr>
<tr>
<td>PANAS-Positive Affect</td>
<td>.620</td>
<td>-.093</td>
<td>.159</td>
<td>-.180</td>
</tr>
<tr>
<td>RFQ-Promotion</td>
<td>.802</td>
<td>.065</td>
<td>-.236</td>
<td>.203</td>
</tr>
<tr>
<td>GRAPES-Reward Expectancy</td>
<td>.814</td>
<td>.112</td>
<td>-.105</td>
<td>.057</td>
</tr>
<tr>
<td>BAS</td>
<td>.145</td>
<td>.876</td>
<td>-.013</td>
<td>-.122</td>
</tr>
<tr>
<td>Neuroticism</td>
<td>-.427</td>
<td>.067</td>
<td>.678</td>
<td>.138</td>
</tr>
<tr>
<td>PANAS-Negative Affect</td>
<td>.088</td>
<td>.000</td>
<td>.894</td>
<td>-.012</td>
</tr>
<tr>
<td>RFQ-Prevention</td>
<td>.272</td>
<td>.091</td>
<td>-.013</td>
<td>.843</td>
</tr>
<tr>
<td>GRAPES-Punishment Expectancy</td>
<td>-.363</td>
<td>-.089</td>
<td>.114</td>
<td>.598</td>
</tr>
<tr>
<td>BIS</td>
<td>-.140</td>
<td>.889</td>
<td>.122</td>
<td>.223</td>
</tr>
</tbody>
</table>

A second factor analysis was conducted where extraction was constrained to two factors, to examine whether these factors would correspond to positive affect/reward-related measures and negative affect/punishment-related measures when constrained. The two-factor solution results are shown in Table 6 and accounted for 46.6% of the variance. The first factor accounted for 28.6% of the variance and was positively related to Extraversion, PANAS-Positive Affect, RFQ-Promotion, and GRAPES-Reward, and was negatively related to Neuroticism, PANAS-Negative Affect, GRAPES-Punishment Expectancy, and BIS. The second factor accounted for 18% of the variance and was positively related to Extraversion, BAS, and BIS, and not strongly related to any other measures. Because this analysis accounted for substantially less variance than the unconstrained analysis and did not reveal the third and fourth factor, relating to negative affect or punishment processing, we chose to conduct personality-behaviour correlations using the four-factor structure.
Table 6. Results of factor analysis on personality measures related to reward and punishment processing. Rotated component matrix, constrained to two components to test whether measures loaded onto two factors, one for reward and one for punishment processing. All measures z-scored.

<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraversion</td>
<td>.545</td>
<td>.582</td>
</tr>
<tr>
<td>PANAS-Positive Affect</td>
<td>.496</td>
<td>.048</td>
</tr>
<tr>
<td>RFQ-Promotion</td>
<td>.761</td>
<td>.250</td>
</tr>
<tr>
<td>GRAPES-Reward Expectancy</td>
<td>.727</td>
<td>.291</td>
</tr>
<tr>
<td>BAS</td>
<td>.058</td>
<td>.836</td>
</tr>
<tr>
<td>Neuroticism</td>
<td>-.718</td>
<td>.090</td>
</tr>
<tr>
<td>PANAS-Negative Affect</td>
<td>-.347</td>
<td>.152</td>
</tr>
<tr>
<td>RFQ-Prevention</td>
<td>.092</td>
<td>.301</td>
</tr>
<tr>
<td>GRAPES-Punishment Expectancy</td>
<td>-.453</td>
<td>-.042</td>
</tr>
<tr>
<td>BIS</td>
<td>-.308</td>
<td>.865</td>
</tr>
</tbody>
</table>

Both factor analyses suggest that the data is well characterized by two factors, one that is generally related to multiple positive affect and reward-related measures, and one that is more specifically related to Extraversion and both BIS and BAS. When the factor analysis is not constrained to two factors, a third and fourth factor appear, with the third factor relating to negative affect and the fourth factor relating to punishment sensitivity. It is of note that while positive affect and reward-related variance loaded onto a common factor, negative affect and punishment-related variance appeared to load onto separate factors (Factors 3 and 4).

We had a priori hypotheses that individual differences in reward sensitivity would correlate with increased proactive control and preparatory pupil dilation under incentive. These analyses are presented here, using the two factors extracted from factor analysis relating to reward sensitivity (Factor 1 relating to Extraversion, PANAS-Positive Affect, RFQ-Promotion, and GRAPES-Reward; and Factor 2 relating to Extraversion, BAS, and BIS), and data from the Reward block (of the Reward session). Exploratory analyses examining relations between these factors and performance/pupil activity in the Positive Emotion block (of the Emotion session), as well as relations between Factors 3 and 4 and
performance/pupil activity in both experimental sessions is presented in the Supplemental Material.

The factor loadings of the first two factors (i.e., Factor 1, Positive Affect/Reward Sensitivity; and Factor 2, Extraversion/BISBAS) were correlated with task performance and pupillometric measures. These correlations are shown in Table 7 (Factor 1) and Table 8 (Factor 2). In terms of task performance measures, we correlated our factor loadings specifically with global error rates and global RTs on reward blocks, and reward rates. No significant correlation between the Pos Affect/Reward factor or the Extraversion/BISBAS factor and any of these raw task performance measures was observed. Next, we calculated proactive indices using RTs and errors for trial conditions of interest (Non-Incentive trials, Incentive trials, Incentive—Non-Incentive) and correlated them with the two reward-related factors: none of the correlations between reward sensitivity measures and proactive indices of performance reached significance.

When examining correlations between the two reward-related factors and pupil activity, pupil magnitudes during the cue maintenance period (2550-2800ms) were examined in Incentive and Non-Incentive trials within the reward block, and Incentive—Non-Incentive (the difference in dilation between the two conditions). Pupil magnitudes were calculated separately for A-cue and B-cue trials. Inconsistent with our hypotheses, the Positive Affect/Reward factor was negatively correlated with Incentive—Non-Incentive pupil dilation at cue maintenance in A-cue trials \( r(82) = -.237, p = .032 \). Also, the Extraversion/BISBAS factor was positively correlated with pupil dilation at cue maintenance in Non-Incentive A-cue trials \( p = .014 \), but not Incentive A-cue trials; this
pattern was not consistent with our hypothesis that reward sensitivity would be more closely related to pupil dilation in incentive, versus non-incentive, trials.

Table 7. Results of correlation analyses between Positive Affect/Reward Sensitivity (Factor 1 emergent from factor analysis of reward and punishment-related individual difference measures) and key measures of performance and pupil activity under incentive.

<table>
<thead>
<tr>
<th>Measures Correlated with Positive Affect/Reward (Factor 1)</th>
<th>Analysis Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reward rate</td>
<td>$r(82) = .063, p = .574$</td>
</tr>
<tr>
<td>Global error rate in reward block</td>
<td>$r(82) = .059, p = .597$</td>
</tr>
<tr>
<td>Global RT in reward block</td>
<td>$r(82) = .031, p = .780$</td>
</tr>
<tr>
<td>Non-Incentive Proactive Index (error rates)</td>
<td>$r(82) = -.060, p = .594$</td>
</tr>
<tr>
<td>Non-Incentive Proactive Index (RTs)</td>
<td>$r(82) = -.079, p = .480$</td>
</tr>
<tr>
<td>Incentive Proactive Index (error rates)</td>
<td>$r(82) = .052, p = .643$</td>
</tr>
<tr>
<td>Incentive Proactive Index (RTs)</td>
<td>$r(82) = -.035, p = .755$</td>
</tr>
<tr>
<td>Incentive—Non-Incentive Proactive Index (error rates)</td>
<td>$r(82) = .089, p = .428$</td>
</tr>
<tr>
<td>Incentive—Non-Incentive Proactive Index (RTs)</td>
<td>$r(82) = -.151, p = .185$</td>
</tr>
<tr>
<td>Non-Incentive pupil activity at cue maintenance (A-cue)</td>
<td>$r(82) = .214, p = .053$</td>
</tr>
<tr>
<td>Non-Incentive pupil activity at cue maintenance (B-cue)</td>
<td>$r(82) = .110, p = .327$</td>
</tr>
<tr>
<td>Incentive pupil activity at cue maintenance (A-cue)</td>
<td>$r(82) = -.074, p = .508$</td>
</tr>
<tr>
<td>Incentive pupil activity at cue maintenance (B-cue)</td>
<td>$r(82) = -.213, p = .055$</td>
</tr>
<tr>
<td>Incentive—Non-Incentive Incentive pupil activity at cue maintenance (A-cue)</td>
<td>$r(82) = -.237, p = .032$</td>
</tr>
<tr>
<td>Incentive—Non-Incentive Incentive pupil activity at cue maintenance (B-cue)</td>
<td>$r(82) = -.192, p = .083$</td>
</tr>
</tbody>
</table>
Table 8. Results of correlation analyses between Extraversion/BISBAS (Factor 2 emergent from factor analysis of reward and punishment-related individual difference measures) and key measures of performance and pupil activity under incentive.

<table>
<thead>
<tr>
<th>Measures Correlated with Extraversion/BISBAS (Factor 2)</th>
<th>Analysis Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reward rate</td>
<td>$r(82) = .156, p = .161$</td>
</tr>
<tr>
<td>Global error rate in reward block</td>
<td>$r(82) = .040, p = .723$</td>
</tr>
<tr>
<td>Global RT in reward block</td>
<td>$r(82) = .077, p = .492$</td>
</tr>
<tr>
<td>Non-Incentive Proactive Index (error rates)</td>
<td>$r(82) = -.049, p = .663$</td>
</tr>
<tr>
<td>Non-Incentive Proactive Index (RTs)</td>
<td>$r(82) = .011, p = .923$</td>
</tr>
<tr>
<td>Incentive Proactive Index (error rates)</td>
<td>$r(82) = .127, p = .254$</td>
</tr>
<tr>
<td>Incentive Proactive Index (RTs)</td>
<td>$r(82) = .004, p = .971$</td>
</tr>
<tr>
<td>Incentive—Non-Incentive Proactive Index (error rates)</td>
<td>$r(82) = .138, p = .217$</td>
</tr>
<tr>
<td>Incentive—Non-Incentive Proactive Index (RTs)</td>
<td>$r(82) = .042, p = .713$</td>
</tr>
<tr>
<td>Non-Incentive pupil activity at cue maintenance (A-cue)</td>
<td>$r(82) = .271, p = .014$</td>
</tr>
<tr>
<td>Non-Incentive pupil activity at cue maintenance (B-cue)</td>
<td>$r(82) = .169, p = .128$</td>
</tr>
<tr>
<td>Incentive pupil activity at cue maintenance (A-cue)</td>
<td>$r(82) = .106, p = .341$</td>
</tr>
<tr>
<td>Incentive pupil activity at cue maintenance (B-cue)</td>
<td>$r(82) = .095, p = .394$</td>
</tr>
<tr>
<td>Incentive—Non-Incentive Incentive pupil activity at cue maintenance (A-cue)</td>
<td>$r(82) = -.174, p = .118$</td>
</tr>
<tr>
<td>Incentive—Non-Incentive Incentive pupil activity at cue maintenance (B-cue)</td>
<td>$r(82) = -.182, p = .101$</td>
</tr>
</tbody>
</table>

Overall, there did not appear to be a pattern of significant correlations between stable reward-related individual differences and task performance/pupil activity. Both the average composite of reward-related measures and both reward-related components from our factor analysis of reward/punishment-related individual differences failed to show a significant positive correlation with task performance and pupil activity; if anything, reward sensitivity was negatively correlated with incentive-related increases in pupil dilation at cue maintenance. Thus, Hypothesis 1 was not confirmed by the observed data.
Hypothesis 2 Analyses: Positive Emotion Induction, Positive Affect/Reward-Related Individual Differences, and Changes in Control in the Positive Emotion Task Block

To address Hypothesis 2’s predictions, that positive emotion was associated with positive affect/reward-related individual differences and a decrease in proactive control, we examined correlations between self-reported (SAM) valence and arousal at timepoint 4 (after the positive emotion induction video and before the positive block) and the first two factors from our factor analysis described in Hypothesis 1 (the Positive Affect/Reward Sensitivity factor and Extraversion/BISBAS factor). We also correlated the SAM ratings at timepoint 4 with the proactive index measures in the positive block (for both neutral and positively valenced trials, calculated via both error rates and RTs). No significant correlations were observed (all p-values > .12).

We next calculated a series of difference scores to correlate in order to further test whether an increased shift towards positive valence with the positive emotion induction (measured via self-report) was associated with a decrease in proactive control. We calculated difference scores in SAM valence and arousal between intervals 3 and 4 of the Emotion session (i.e., the difference in mood valence and arousal as a function of viewing the positive emotion induction video) and correlated these difference scores with factor scores (Positive Affect/Reward and Extraversion/BISBAS) as well as with differences in proactive indices (calculated via error rates and RTs) between the neutral block and neutral trials within positive blocks of the Emotion session (i.e., positive context effect).

Two significant correlations were revealed by these analyses. A significant positive correlation was observed between changes in emotion arousal at this interval and the Positive Affect/Reward factor \( r(82) = .306, p = .005 \); shown in Figure 22a]. Second, a
significant negative correlation was observed between changes in emotion valence and differences in the proactive index with emotion block [\(r(96) = -.210, p = .04\); shown in Figure 22b]. The higher participants scored on the Positive Affect/Reward factor, the larger their arousal increase with the positive video; and the more that participants reported their mood valence increasing with the positive video induction, the more proactive control decreased from the neutral to the positive emotion block. The higher participants scored on the Positive Affect/Reward factor, the larger their arousal increase with the positive video; this is somewhat consistent with the predictions of Hypothesis 2, although a significant correlation with valence would have been more expected. More puzzling is the second correlation, which suggests that the more that participants reported their mood valence increasing with the positive video induction, the more proactive control decreased from the neutral to the positive emotion block. It should be noted that this correlation is not that robust; when a single subject showing a large decrease in proactive control from neutral to positive block (-0.5; visible in Figure 15b) was removed, the significance of this correlation dropped from \(p = .04\) to \(p = .204\). This subject did not meet outlier criteria and remains in the analysis, but results should be interpreted with caution.
Figure 22. Scatterplots showing significant relationships between changes in self-reported emotion (via SAM assessment) with positive emotion induction and task performance/individual differences: (a) Positive Affect/Reward Sensitivity (as defined by factor analysis of individual difference measures) was positively correlated with increased emotional arousal with positive emotion induction (N=82, p = .005); (b) Increased proactive control (measured with RT proactive indices) in the positive emotion block, relative to neutral block, was negatively correlated with increased emotion valence with positive emotion induction (N=96, p = .04).

Task Performance and Pupil Activity in Top Thirty Reward Sensitive Individuals

Following up on the observation that the Positive Affect/Reward Sensitivity factor was correlated with higher reported arousal after the positive emotion induction, we also examined performance and pupil measures in a subsection (N=30) of our sample scoring the highest on this factor. The goal of this analysis was to test whether focusing only on the most reward-responsive individuals showed (1) any evidence of a larger positive emotion effect on behaviour or pupil activity; or (2) any differences in the relationship between Emotion and Reward conditions, relative to the full sample. The mean score on this factor
in the top 30 reward sensitive individuals was 2.90 +/- 0.15, as opposed to 0.51 +/- 0.24 in the full sample.

For the most part, the top thirty reward sensitive individuals did not show appreciably greater effects, and sometimes showed smaller effects, of emotion or reward incentive on AX-CPT task performance or related pupil dilation during either the Reward or Emotion session. For example, increases in error proactive indices were actually greater in the full sample, with both block-based reward effects (difference scores of 0.1483 in the top thirty group, compared to 0.2064 in the full sample), and trial-based effects (difference scores of 0.1781 in the top thirty group, compared to 0.2237 in the full sample). Transient pupil dilation increased slightly more under incentive, relative to non-incentive trials, in the full sample than in the top thirty group (difference scores of 3.68% in the top thirty group, compared to 5.42% in the full sample). Block-based pupil activity increased more under incentive in the top thirty group than in the full sample (Reward-Baseline block difference scores of 442.3 in the top thirty group, compared to 184.8 in the full sample), but given the lack of evidence in other measures that reward sensitivity was associated with increased incentive effects this finding should be interpreted with caution. Results of the positive emotion manipulation also looked relatively similar in the top thirty group compared to the full sample, with similarly small changes in error proactive indices as a function of emotional task block (difference scores of 0.028 in the top thirty group, compared to 0.077 in the full sample) and similarly small increases in pretrial pupil diameter as a function of block (Positive—Neutral block difference scores of 289.7285 in the top thirty group, compared to 211.1685 in the full sample). Means of performance and pupil measures (proactive indices, pupil dilation at cue maintenance, and pretrial pupil
diameters) are shown comparatively for the top thirty group, compared to the full sample, in Table 9.

Table 9. Comparison between top 30 reward sensitive individuals versus full sample on proactive indices (calculated using error rates and RTs) and pupil activity (transient pupil at cue maintenance and pretrial pupil diameter) as a function of emotion and reward manipulations. All values listed as means +/- standard error.

<table>
<thead>
<tr>
<th>Proactive Index (Error Rates)</th>
<th>Top 30 Reward Sensitive Individuals</th>
<th>Full Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Trials</td>
<td>0.2830 +/- 0.07</td>
<td>0.1951 +/- 0.04</td>
</tr>
<tr>
<td>Non-Incentive Trials</td>
<td>0.4313 +/- 0.05</td>
<td>0.4015 +/- 0.04</td>
</tr>
<tr>
<td>Incentive Trials</td>
<td>0.6094 +/- 0.06</td>
<td>0.6252 +/- 0.03</td>
</tr>
<tr>
<td>Neutral Trials</td>
<td>0.2262 +/- 0.06</td>
<td>0.2089 +/- 0.04</td>
</tr>
<tr>
<td>Neutral Trials in Positive Block</td>
<td>0.2542 +/- 0.06</td>
<td>0.2862 +/- 0.04</td>
</tr>
<tr>
<td>Positive Trials</td>
<td>0.2942 +/- 0.06</td>
<td>0.2364 +/- 0.04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proactive Index (RTs)</th>
<th>Top 30 Reward Sensitive Individuals</th>
<th>Full Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Trials</td>
<td>0.2853 +/- 0.02</td>
<td>0.2875 +/- 0.01</td>
</tr>
<tr>
<td>Non-Incentive Trials</td>
<td>0.3202 +/- 0.02</td>
<td>0.3272 +/- 0.01</td>
</tr>
<tr>
<td>Incentive Trials</td>
<td>0.3118 +/- 0.02</td>
<td>0.3150 +/- 0.03</td>
</tr>
<tr>
<td>Neutral Trials</td>
<td>0.2925 +/- 0.02</td>
<td>0.2914 +/- 0.01</td>
</tr>
<tr>
<td>Neutral Trials in Positive Block</td>
<td>0.2981 +/- 0.02</td>
<td>0.2687 +/- 0.01</td>
</tr>
<tr>
<td>Positive Trials</td>
<td>0.2988 +/- 0.02</td>
<td>0.3157 +/- 0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transient Pupil Activity at Cue Maintenance Period (2550-2800ms; % change from baseline)</th>
<th>Top 30 Reward Sensitive Individuals</th>
<th>Full Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline A-Cue Trials</td>
<td>-2.0324 +/- 0.13</td>
<td>-1.3245 +/- 0.49</td>
</tr>
<tr>
<td>Baseline B-Cue Trials</td>
<td>0.0075 +/- 0.71</td>
<td>0.0795 +/- 0.34</td>
</tr>
<tr>
<td>Non-Incentive A-Cue Trials</td>
<td>-1.9713 +/- 0.56</td>
<td>-2.6012 +/- 0.58</td>
</tr>
<tr>
<td>Non-Incentive B-Cue Trials</td>
<td>-2.5653 +/- 1.66</td>
<td>-2.1664 +/- 0.89</td>
</tr>
<tr>
<td>Incentive A-Cue Trials</td>
<td>-0.364 +/- 0.89</td>
<td>0.5712 +/- 0.42</td>
</tr>
<tr>
<td>Incentive B-Cue Trials</td>
<td>1.1124 +/- 1.06</td>
<td>3.2589 +/- 0.60</td>
</tr>
<tr>
<td>Neutral A-Cue Trials</td>
<td>-0.7009 +/- 0.63</td>
<td>-0.6633 +/- 0.38</td>
</tr>
<tr>
<td>Neutral B-Cue Trials</td>
<td>-0.6335 +/- 1.01</td>
<td>-0.3072 +/- 0.48</td>
</tr>
<tr>
<td>Neutral A-Cue Trials in Positive Block</td>
<td>-1.0537 +/- 0.90</td>
<td>-2.3181 +/- 0.83</td>
</tr>
<tr>
<td>Neutral B-Cue Trials in Positive Block</td>
<td>-0.4492 +/- 0.92</td>
<td>-0.9389 +/- 0.64</td>
</tr>
<tr>
<td>Positive A-Cue Trials</td>
<td>-0.4304 +/- 1.14</td>
<td>-2.1833 +/- 0.56</td>
</tr>
<tr>
<td>Positive B-Cue Trials</td>
<td>1.0688 +/- 1.66</td>
<td>-1.2898 +/- 0.66</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pretrial Pupil Activity (-200-0ms; in raw units)</th>
<th>Top 30 Reward Sensitive Individuals</th>
<th>Full Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Block</td>
<td>4324.0392 +/- 158.89</td>
<td>4708.388 +/- 98.34</td>
</tr>
<tr>
<td>Reward Block</td>
<td>4766.3783 +/- 156.27</td>
<td>4893.2131 +/- 96.09</td>
</tr>
<tr>
<td>Neutral Block</td>
<td>4432.4474 +/- 255.30</td>
<td>4488.511 +/- 99.21</td>
</tr>
<tr>
<td>Positive Block</td>
<td>4722.1759 +/- 185.76</td>
<td>4699.6795 +/- 104.80</td>
</tr>
</tbody>
</table>

In analyses testing for significant differences in performance/pupil as a result of experimental manipulations, the top thirty group did not appear to show stronger effects than present in the full sample. (For full comparison of significant results between the top
thirty group and the full sample, please refer to Tables 10, 11, and 12.) Emotion and reward effects tended to reach significance more in the full sample (not surprising given the lower

Table 10. Comparison between task performance in top 30 reward sensitive individuals versus full sample with error rates as a dependent measure: significant ($p < .05$) results listed, with effect sizes.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Effect in Top 30 Reward Sensitive individuals (with effect size)</th>
<th>Effect in full sample (with effect size)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Task Performance: Block-Based Effects in Reward AX-CPT</strong></td>
<td>Block (RW&gt;BL; $\eta^2 = 0.038$)</td>
<td>Block (RW&gt;BL; $\eta^2 = 0.094$)</td>
</tr>
<tr>
<td></td>
<td>Cue (A&gt;B; $\eta^2 = 0.197$)</td>
<td>Cue (A&gt;B; $\eta^2 = 0.142$)</td>
</tr>
<tr>
<td></td>
<td>Probe (Y&gt;X; $\eta^2 = 0.264$)</td>
<td>Probe (Y&gt;X; $\eta^2 = 0.147$)</td>
</tr>
<tr>
<td></td>
<td>Block*Cue (A&gt;B more in RW; $\eta^2 = 0.10$)</td>
<td>Block*Cue (A&gt;B more in RW; $\eta^2 = 0.085$)</td>
</tr>
<tr>
<td></td>
<td>Block*Probe (Y&gt;X more in RW; $\eta^2 = 0.083$)</td>
<td>Block*Probe (Y&gt;X more in RW; $\eta^2 = 0.043$)</td>
</tr>
<tr>
<td></td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.254$)</td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.222$)</td>
</tr>
<tr>
<td></td>
<td>Block<em>Cue</em>Probe (AY &gt; others more in RW; $\eta^2 = 0.0371$)</td>
<td>Block<em>Cue</em>Probe (AY &gt; others more in RW; $\eta^2 = 0.103$)</td>
</tr>
<tr>
<td><strong>Task Performance: Trial-Based Effects in Reward AX-CPT</strong></td>
<td>Incentive (INC&gt;NONINC; $\eta^2 = 0.044$)</td>
<td>Incentive (INC&gt;NONINC; $\eta^2 = 0.039$)</td>
</tr>
<tr>
<td></td>
<td>Cue (A&gt;B; $\eta^2 = 0.448$)</td>
<td>Cue (A&gt;B; $\eta^2 = 0.442$)</td>
</tr>
<tr>
<td></td>
<td>Probe (Y&gt;X; $\eta^2 = 0.458$)</td>
<td>Probe (Y&gt;X; $\eta^2 = 0.422$)</td>
</tr>
<tr>
<td></td>
<td>Incentive*Cue (A&gt;B bigger in INC; $\eta^2 = 0.116$)</td>
<td>Incentive*Cue (A&gt;B bigger in INC; $\eta^2 = 0.10$)</td>
</tr>
<tr>
<td></td>
<td>Incentive*Probe (Y&gt;X bigger in INC; $\eta^2 = 0.073$)</td>
<td>Incentive*Probe (Y&gt;X bigger in INC; $\eta^2 = 0.114$)</td>
</tr>
<tr>
<td></td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.456$)</td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.448$)</td>
</tr>
<tr>
<td></td>
<td>Incentive<em>Cue</em>Probe (AY &gt; others bigger in INC; $\eta^2 = 0.139$)</td>
<td>Incentive<em>Cue</em>Probe (AY &gt; others bigger in INC; $\eta^2 = 0.085$)</td>
</tr>
<tr>
<td><strong>Task Performance: Block-Based Effects in Emotion AX-CPT</strong></td>
<td>Block (NEUT&gt;POS; $\eta^2 = 0.029$)</td>
<td>Block (trend; NEUT&gt;POS; $\eta^2 = 0.005$)</td>
</tr>
<tr>
<td></td>
<td>Cue (A&gt;B; $\eta^2 = 0.118$)</td>
<td>Cue (A&gt;B; $\eta^2 = 0.071$)</td>
</tr>
<tr>
<td></td>
<td>Probe (Y&gt;X; $\eta^2 = 0.103$)</td>
<td>Probe (Y&gt;X; $\eta^2 = 0.09$)</td>
</tr>
<tr>
<td></td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.152$)</td>
<td>Block*Cue (A&gt;B more in POS; $\eta^2 = 0.016$)</td>
</tr>
<tr>
<td><strong>Task Performance: Trial-Based Effects in Emotion AX-CPT</strong></td>
<td>Cue (A&gt;B; $\eta^2 = 0.213$)</td>
<td>Block*Probe (Y&gt;X more in POS; $\eta^2 = 0.068$)</td>
</tr>
<tr>
<td></td>
<td>Probe (Y&gt;X; $\eta^2 = 0.198$)</td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.159$)</td>
</tr>
<tr>
<td></td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.203$)</td>
<td>Cue (A&gt;B; $\eta^2 = 0.114$)</td>
</tr>
<tr>
<td><strong>Task Performance: Block-Based Effects on Task Performance: Emotion vs. Reward Session (on Proactive Indices)</strong></td>
<td>Session (REW &gt; EMO; $\eta^2 = 0.046$)</td>
<td>Session*Block (Block 2 &gt; Block 1; $\eta^2 = 0.049$)</td>
</tr>
<tr>
<td><strong>Task Performance: Trial-Based Effects on Task Performance: Emotion vs. Reward Session (on Proactive Indices)</strong></td>
<td>Session (REW &gt; EMO; $\eta^2 = 0.182$)</td>
<td>Session (REW&gt;EMO; $\eta^2 = 0.179$)</td>
</tr>
<tr>
<td></td>
<td>Trial (INC/POS &gt; NONINC/NEUT; $\eta^2 = 0.048$)</td>
<td>Trial (INC/POS &gt; NONINC/NEUT; $\eta^2 = 0.028$)</td>
</tr>
<tr>
<td></td>
<td>Session*Trial (INC/POS&gt;NONINC/NEUT trial effect larger in REW than EMO; $\eta^2 = 0.070$)</td>
<td>Session*Trial (INC/POS&gt;NONINC/NEUT trial effect larger in REW than EMO; $\eta^2 = 0.070$)</td>
</tr>
</tbody>
</table>
Table 11. Comparison between task performance in top 30 reward sensitive individuals versus full sample with RTs as a dependent measure: significant ($p < .05$) results listed, with effect sizes.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Effect in Top 30 Reward Sensitive individuals (with effect size)</th>
<th>Effect in full sample (with effect size)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Task Performance:</strong></td>
<td><strong>Block-Based Effects in Reward AX-CPT</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Block (BL&gt;RW; $\eta^2 = 0.158$)</td>
<td>Block (BL-RW; $\eta^2 = 0.165$) Adam (A&gt;B; $\eta^2 = 0.546$)</td>
</tr>
<tr>
<td></td>
<td>Probe (Y&gt;X; $\eta^2 = 0.342$)</td>
<td>Probe (Y&gt;X; $\eta^2 = 0.319$) Cue*Probe (AY &gt; others; $\eta^2 = 0.236$)</td>
</tr>
<tr>
<td></td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.236$)</td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.237$) Cue (A&gt;B; $\eta^2 = 0.547$)</td>
</tr>
<tr>
<td><strong>Task Performance:</strong></td>
<td><strong>Trial-Based Effects in Reward AX-CPT</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Incentive (NONINC&gt; INC; $\eta^2 = 0.172$)</td>
<td>Incentive (NONINC &gt; INC; $\eta^2 = 0.165$) Cue (A&gt;B; $\eta^2 = 0.636$)</td>
</tr>
<tr>
<td></td>
<td>Probe (Y&gt;X; $\eta^2 = 0.376$)</td>
<td>Probe (Y&gt;X; $\eta^2 = 0.392$) Cue*Probe (AY &gt; others; $\eta^2 = 0.355$)</td>
</tr>
<tr>
<td></td>
<td>Inc*Cue (A&gt;B larger in INC; $\eta^2 = 0.012$)</td>
<td></td>
</tr>
<tr>
<td><strong>Task Performance:</strong></td>
<td><strong>Trial-Based Effects in Reward AX-CPT</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cue (A&gt;B; $\eta^2 = 0.580$)</td>
<td>Cue (A&gt;B; $\eta^2 = 0.496$) Probe (Y&gt;X; $\eta^2 = 0.289$)</td>
</tr>
<tr>
<td></td>
<td>Probe (Y&gt;X; $\eta^2 = 0.355$)</td>
<td>Probe (Y&gt;X; $\eta^2 = 0.289$) Cue*Probe (AY &gt; others; $\eta^2 = 0.278$)</td>
</tr>
<tr>
<td></td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.319$)</td>
<td></td>
</tr>
<tr>
<td><strong>Task Performance:</strong></td>
<td><strong>Trial-Based Effects in Reward AX-CPT</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cue (A&gt;B; $\eta^2 = 0.555$)</td>
<td>Emotion (trend POS&gt;NEUT; $\eta^2 = 0.002$) Cue (A&gt;B; $\eta^2 = 0.527$)</td>
</tr>
<tr>
<td></td>
<td>Probe (Y&gt;X; $\eta^2 = 0.356$)</td>
<td>Probe (Y&gt;X; $\eta^2 = 0.312$) Emotion*Cue (faster B trials in POS; $\eta^2 = 0.002$)</td>
</tr>
<tr>
<td></td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.328$)</td>
<td>Cue*Probe (AY &gt; others; $\eta^2 = 0.298$) Session (REW &gt; EMO; $\eta^2 = 0.008$)</td>
</tr>
<tr>
<td><strong>Task Performance:</strong></td>
<td><strong>Task Performance: Block-Based Effects on Emotion AX-CPT</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No sig effects; same direction as in full dataset</td>
<td>Session*Block (Block 2 &gt; Block 1 effect much larger in REW session than in EMO; $\eta^2 = 0.012$)</td>
</tr>
<tr>
<td><strong>Task Performance:</strong></td>
<td><strong>Task Performance: Trial-Based Effects on Emotion AX-CPT</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No sig effects</td>
<td>No sig effects</td>
</tr>
</tbody>
</table>
Table 12. Comparison between task performance in top 30 reward sensitive individuals versus full sample with pupil activity as a dependent measure: significant \((p < .05)\) results listed, with effect sizes.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Effect in Top 30 Reward Sensitive individuals</th>
<th>Effect in full sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pupil Activity: Block Effects in Reward Session</td>
<td>Sig (RW &gt; BL; (\eta^2 = 0.05))</td>
<td>Sig (RW &gt; BL; (\eta^2 = 0.01))</td>
</tr>
<tr>
<td>Pupil Activity: Transient Effects in Reward Session</td>
<td>Incentive (INC &gt; NONINC; (\eta^2 = 0.061))</td>
<td>Incentive (INC&gt;NONINC; (\eta^2 = .119))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cue (B&gt;A; (\eta^2 = 0.029))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Incentive*Cue (B&gt;A more in INC; (\eta^2 = 0.014))</td>
</tr>
<tr>
<td>Pupil Activity: Block Effects in Emotion Session</td>
<td>Sig (Pos &gt; Neut; (\eta^2 = 0.015))</td>
<td>Sig (Pos &gt; Neut; (\eta^2 = 0.007))</td>
</tr>
<tr>
<td>Pupil Activity: Transient Effects in Emotion Session</td>
<td>No sig effects</td>
<td>Cue (B&gt;A; (\eta^2 = 0.009))</td>
</tr>
<tr>
<td>Pupil Activity: Block Effects in Emotion vs. Reward Session</td>
<td>Block (Block 2 &gt; Block1; (\eta^2 = 0.039))</td>
<td>Session (REW &gt; EMO; (\eta^2 = 0.077))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Block (Block 2 &gt; Block 1; (\eta^2 = 0.079))</td>
</tr>
<tr>
<td>Pupil Activity: Transient Effects in Emotion vs. Reward Session</td>
<td>Trial (INC/POS &gt; NONINC/NEUT; (\eta^2 = 0.055))</td>
<td>Session (REW &gt; EMO; (\eta^2 = 0.02))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trial (INC/POS &gt; NONINC/NEUT; (\eta^2 = 0.057))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cue (B&gt;A; (\eta^2 = 0.03))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Session x Trial (INC/POS &gt; NONINC/NEUT effect bigger in REW; (\eta^2 = 0.059))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Session x Trial x Cue (INC B-cue pupil &gt; all other conditions; (\eta^2 = 0.008))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reward: BL &gt; NONINC ((\eta^2 = 0.02))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Emotion: NEUT &gt; NEUTPOS (trend; (\eta^2 = 0.014))</td>
</tr>
</tbody>
</table>

power of the sub-sample), but effect sizes, which are listed for each significant effect in Tables 10-12, are not dependent on sample size and did not suggest a definitive pattern of larger effects in the top thirty subsample. In general, the patterns of results appeared to be qualitatively similar in the top thirty participants, relative to the full sample: relationships between emotion/reward manipulations and outcome measures appeared to be generally the same, without major differences in the patterns of significant effects reported or effect sizes.
Hypothesis 3 Analyses: Working Memory Capacity, Cognitive Control, & Pupil Activity

Hypothesis 3 encompassed several predictions that we wanted to examine. (1) Working memory capacity is related to more proactive control in baseline/neutral conditions. (2) Low WMC individuals might exert less mental effort than high WMC individuals in baseline/neutral conditions, and this is associated with smaller tonic pupil diameter in these individuals. (3) Incentive-related increases in mental effort are similar across both low and high WMC individuals, and thus changes in pupil dilation as a function of incentive should not relate to WMC. These hypotheses were based on evidence indicating that working memory capacity is positively correlated with task maintenance and proactive control as well as findings that high WMC individuals had larger tonic pupil diameters than low WMC individuals during a task block, but both high and low WMC individuals may show similar incentive-evoked changes in pupil dilation (Heitz et al., 2008).

As a measure of working memory capacity to use in these analyses, we chose to use partial storage score from the Automated O-span Task (Unsworth et al., 2005). The O-span requires that participants view letters interspersed with arithmetic problems on each trial, and then recall the letter string in the serial order presented. Scoring performance produces both an absolute storage score and a partial storage score: absolute storage score is the sum of trials where all items are recalled in the correct order, while partial storage score is the sum of items recalled in the correct order, whether or not the entire trial was recalled correctly. We chose to use partial storage score as a measure of WMC due to its superior psychometric properties: it has been found to have higher internal consistencies and stronger relationships to other cognitive measures (reviewed in Redick et al., 2012). Complete O-span data was present for 80 subjects. All variables were checked for outliers
using the ESD method prior to analysis. Two subjects were identified as outliers and eliminated due to low O-span scores, leaving N=78 used in WMC-behaviour/pupil correlations.

We again used proactive index measures, calculated for error rates and RTs as previously described, as a measure of proactive control. The O-span partial storage score was correlated with proactive indices only for the Neutral and Baseline blocks, given that we had no evidence from previous literature that the relationship between WMC and cognitive control would change under emotion or reward. When we correlated WMC (measured with O-span partial storage score) with neutral and baseline block proactive indices, no significant correlations were observed. We followed these analyses with exploratory correlations examining the relationships between WMC and raw error and RT measures in the Neutral and Baseline blocks. We observed a significant negative correlation between WMC and global RTs in the Baseline block \[ r(77) = -.306, p = .007 \]. This correlation is shown in Figure 23 and suggests that in the present data, higher WMC was associated with better performance at baseline (in terms of faster RTs) but not specifically with greater proactive control. Given that the effect did not reach significance in the neutral block, in which performance was hypothesized to have a similar relation with WMC, this finding should be interpreted with caution.
We also followed analyses by Richmond and colleagues (Richmond, Redick, & Braver, 2012) that showed that WMC was predictive of enhanced proactive control during task performance, when BY performance was controlled for as a non-specific measure of processing speed. Specifically, Richmond and colleagues observed that when BY performance was controlled for, WMC was a negative predictor of AY performance and a positive predictor of AX and BX performance; this is consistent with predicting the use of proactive control in that such control is associated with worse performance on AY trials, and improved performance on all other trial types. With AX, AY and BX performance measures in the Baseline and Neutral blocks each serving as dependent variables, hierarchical regression was employed, with performance on BY trials entered as the first step and then WMC as the second step. This method was employed for both accuracy and RT analyses. Results are shown in Table 13. While these results indicate that WMC was a significant predictor in some analyses, particularly for RTs, beta values for significant and trend-level predictors tended to be negative across trial types including AY trials. This
pattern suggests that in the present data, WMC was associated with faster performance in general but not specifically with proactive control.

Table 13. Results of hierarchical regressions examining the relationship between WMC (O-Span Total) and AX, AY and BX trial performance in Baseline and Neutral blocks, controlling for BY performance (i.e., with BY performance entered at the first step in the regression and WMC entered at the second step). BY performance was strongly predictive of AX, AY and BX performance, hence the highly significant model F overall; WMC was a much smaller predictor of performance, but reached significance in certain analyses. Notation is as follows: ‡p < .10, *p < .05, **p < .01, ***p < .001

<table>
<thead>
<tr>
<th>Dependent Measure Predicted by WMC (O-Span Total) in Regression, Controlling for BY Performance</th>
<th>Analysis Results (for Model 2, with WMC entered as a predictor after BY performance)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model F</td>
</tr>
<tr>
<td>Baseline block AX error rate</td>
<td>56.230***</td>
</tr>
<tr>
<td>Baseline block AY error rate</td>
<td>12.067***</td>
</tr>
<tr>
<td>Baseline block BX error rate</td>
<td>36.458***</td>
</tr>
<tr>
<td>Baseline block AX RTs</td>
<td>29.915***</td>
</tr>
<tr>
<td>Baseline block AY RTs</td>
<td>12.582***</td>
</tr>
<tr>
<td>Baseline block BX RTs</td>
<td>85.988***</td>
</tr>
<tr>
<td>Neutral block AX error rate</td>
<td>48.204***</td>
</tr>
<tr>
<td>Neutral block AY error rate</td>
<td>8.017**</td>
</tr>
<tr>
<td>Neutral block BX error rate</td>
<td>12.717***</td>
</tr>
<tr>
<td>Neutral block AX RTs</td>
<td>22.038***</td>
</tr>
<tr>
<td>Neutral block AY RTs</td>
<td>37.629***</td>
</tr>
<tr>
<td>Neutral block BX RTs</td>
<td>63.392***</td>
</tr>
</tbody>
</table>

We then investigated whether higher WMC was associated with greater tonic pupil activity, following observations by Heitz and colleagues (Heitz et al., 2008), by correlating WMC (partial storage score on the O-Span) with pupil activity in the pretrial period (-200-0ms, calculated in raw pupil units) in the Neutral and Baseline blocks. Neither of these correlations reached significance. Finally, we investigated whether increases in pupil dilation with incentive differed as a function of WMC by correlating WMC (partial storage score on the O-Span) with the Incentive—Non-Incentive pupil dilation at cue maintenance period for A-cues and B-cues (2550-2800ms; i.e., the extent to which pupil dilation increased with incentive relative to non-incentive), extracted both as a percentage change measure from baseline and in raw units. None of these correlations reached significance.
To replicate Heitz’s analyses more closely, we re-ran all the previous correlations (with task performance measures and pupil measures) using O-Span absolute storage score instead of partial storage score as a measure of WMC (as done in Heitz et al., 2008). The analysis outcomes were in accordance with those using partial storage score as a correlate (i.e., the same correlations reached statistical significance/insignificance as in the previous analyses).

In conclusion, correlations relating WMC to performance and pupil activity in the present task suggest that WMC was related to faster performance but not specifically with greater proactive control. Additionally, we observed no significant correlations between WMC and measures of pupil activity at pretrial, failing to replicate findings by Heitz and colleagues (Heitz et al., 2008). However, increase in pupil dilation in response to incentive had no significant relation with WMC, which is similar to Heitz’s results, where increases in pupil dilation with incentive occurred regardless of WMC group status.

Hypothesis 4 Analyses: Trait Anxiety, Cognitive Control, and Pupil Dilation

In this series of analyses we sought to examine whether trait anxiety was related to reactive control and pupil activity in the present data. We hypothesized that trait anxiety would be negatively correlated with proactive control. This prediction is based on the cognitive efficiency hypothesis, which posits that high-anxiety individuals consume mental resources by worrying and require greater brain activity to support equivalent cognitive performance, thus being less efficient cognitively than low-anxiety individuals (Eysenck & Calvo, 1992), and related neuroimaging data suggesting that high-anxiety individuals show reduced sustained brain activity and increased transient brain activity during equivalent
performance in a working memory task compared to low-anxiety individuals (Fales et al., 2008) – an activity pattern consistent with the idea that high-anxiety individuals are less efficient cognitively and engage proactive control to a lesser extent. To test this hypothesis, we correlated Trait Anxiety scores from the STAI with proactive indices of performance (calculated with both error rates and RTs) from the Baseline and Neutral blocks. 83 participants had Trait Anxiety data (no outliers were identified). No significant correlations were observed (all \( p \)-values > .07). We also conducted correlations between State Anxiety and these proactive indices (on an exploratory basis) and observed no significant correlations (all \( p \)-values > .11).

We also conducted correlations between Trait Anxiety and pupil activity. Given that we had no strong hypotheses about the relationship between anxiety and pupil response in the present task, these exploratory analyses are available in the Supplementary Material.

**Discussion**

The present study aimed to clarify the relationship between positive emotion and reward motivational incentives by examining their influences on cognitive control using task performance and high-resolution pupillometry, and how the relationships between emotional/reward manipulations and cognitive control related to stable individual differences. Influences of positive emotion and reward incentives have shown diverging effects on cognitive control dynamics in previous literature, but these effects have yet to be directly compared in a study with experimental designs matched as closely as possible. Further, the present study utilized pupillometry as an index of cognitive control dynamics at a high temporal resolution, and involved a large sample with adequate statistical power.
to examine the impact of individual differences on emotion/motivation-cognition interactions. In this investigation, we aimed to replicate our previous findings (Chiew and Braver, 2013) that reward incentives were associated with increased proactive control, directly compare effects of positive emotion and reward incentive on cognitive control, and explore the influence of individual differences on these interactions. We discuss the findings of the present study here, implications and limitations of the present data, and directions for future research.

Aim 1: Effects of Reward Incentive and Positive Emotion Manipulations on Performance and Pupil Activity

The first aim of the present study was to examine the effects of positive emotion and reward manipulations on cognitive control through task performance and pupillometry. Results from the Reward session are a close replication of Chiew and Braver (2013). Moreover, they are highly consistent with other previous studies examining the effects of reward incentives on cognitive control, indicating that incentive was associated with a shift towards enhanced proactive control, relative to baseline conditions (Jimura et al., 2010; Locke & Braver, 2008; Padmala & Pessoa, 2011; Savine et al., 2010). This replication provided important assurance that the validity and quality of data from the present sample was consistent with previous work. Increased proactive control with incentive generally led to a general enhancement in task performance: lower error rates and faster RTs overall, occurring both in the block-based (contextual) incentive contrast and in the trial-based incentive manipulation (occurring within the reward block). However, enhanced performance was not uniform across all trial types: faster RTs were notably accompanied
by sharp increases in AY errors with incentive context, and further with trial-by-trial incentive. Increased AY errors under incentive are actually consistent with increased proactive utilization of contextual cue information. In contrast, errors in BX trials decreased with incentive, with incentive context as well as with trial-by-trial incentive. Along with the decrease in error rates, BX trial RTs decreased with incentive to near-optimal performance, again with both incentive context and trial-by-trial incentive. This shift towards proactive control was quantified by analysis of proactive index measures, which significantly increased at both the block and trial-based level with incentive. Changes in pupil activity with incentive also replicated Chiew and Braver (2013). Incentive was associated with increased pupil diameter, both on a sustained basis and on a transient, trial-by-trial basis. Replicating previous results, increased pupil dilation was observed on a transient basis on incentive trials, relative to non-incentive trials, within the reward block. Importantly, this increase emerged during cue maintenance, prior to probe onset (and thus, response execution); i.e., in a preparatory or proactive fashion.

In contrast to the relatively consistent previous evidence and robust hypotheses tested regarding the effects of reward incentives on cognitive control, evidence regarding positive emotion on cognitive control has been more mixed and our hypotheses on positive emotion were thus more tentative. As outlined in the Introduction section, we identified three possible, diverging hypotheses to test in the present data: that positive emotion may (1) promote cognitive flexibility and reactive control; (2) result in a null effect on performance (and potentially pupil dilation as well); (3) promote goal pursuit and proactive control. Present data show that effects of the positive emotion manipulation on cognitive control showed a different profile from that of the reward incentive manipulation,
with much weaker effects than those observed in response to reward manipulations. Observed results were not consistent with the hypothesis that positive emotion promotes cognitive flexibility and reactive control. Instead, the changes observed in AX-CPT performance as a function of positive emotion manipulation were somewhat suggestive of a shift towards greater proactive control. In the trial-based emotion contrast (positive trials compared to neutral trials within the reward block), we observed changes in RTs consistent with increased proactive control under positive emotion (slower RTs in AY trials, faster RTs in all other trial types). The magnitude of this effect was small (<10ms changes in RTs) but, when RT proactive indices were calculated and analyzed, the trial-based emotion contrast reached significance. We also observed higher AY errors and lower errors in other trials as a result of the block-based emotional contrast (i.e., in neutral trials in the positive block, compared to neutral block trials), but when this contrast was analyzed using proactive indices calculated from error rates, it did not reach significance. Positive emotion effects on pupil activity did not neatly correspond to task performance: while transient pupil activity did not significantly change with trial-by-trial emotion manipulation, block-based emotion effects were significant (i.e., tonic pupil diameter was higher in the positive block than in the neutral block).

Self-report of emotion, as indexed by Self Assessment Manikins, indicated that the positive emotion induction videos increased experienced emotion valence as anticipated, helping validate the claim that block-based differences in performance/pupil in the Emotion session (e.g., differences between the Neutral and Positive block) were due to changes in emotion. Self Assessment Manikin measures in the Reward session did not show a corresponding increase in emotion valence with induction (as anticipated because only
neutrally-valenced videos were used), but otherwise showed a pattern of self-reported emotion similar to that in the Emotion session. Given that the reward manipulation was associated with smaller changes in self-reported emotion, it is intriguing that it had much stronger effects on performance and pupil outcomes than the emotion manipulation. This is consistent with previous observations that positive mood had weak effects on cognitive control performance (van Wouwe et al., 2009) and in terms of Berridge’s ‘liking/wanting’ dichotomy, it suggests that processes related to ‘wanting’ (i.e., goal-drive related processes) influence cognitive control to a greater extent than processes related to ‘liking’ (i.e., hedonic experience).

Also, consistent with findings from our previous work (Chiew and Braver, 2013), the present data indicates that pupil activity is sensitive to reward and emotional influences, on both tonic and phasic timescales. Phasic pupil activity rises during the cue maintenance period of the trial and this rise increases with incentive (but not positive emotion), consistent with the account that it may be a psychophysiological marker of preparatory / proactive cognitive processes that become enhanced with incentive. This interpretation is further strengthened by pupil-behaviour correlation analyses, which suggest that increased pupil dilation at the cue maintenance (preparatory) period predicts increased proactive control in behavioural performance, particularly on B-cue trials. In contrast, tonic pupil activity increased with both reward and positive emotion manipulations. While reward incentive was associated with robust block-based changes in performance that corresponded to this tonic pupil change, the increase in pupil diameter with emotion occurred in the absence of robust behavioural changes (i.e., while patterns in error rates suggested a small increase in proactive control with positive emotion, proactive index...
measures did not significantly differ between emotion task blocks). This may reflect the presence of more tonic influences, such as arousal or mood, which may not necessarily be directly linked to cognitive performance.

Taken in sum, these patterns of results clearly indicate that pupil dilation is more complex than a simple indicator of mental effort, or as a measure of experienced arousal, alone. Tonic pupil dilation was associated with the positive emotion manipulation in the absence of large overt behavioural changes; an account of pupil dilation as an indicator of mental effort does not account for these findings. Likewise, self-reported levels of arousal (via SAM assessments) were higher under the emotion manipulation than the reward manipulation, but significant increases in tonic pupil dilation were observed in both the positive and reward task runs, relative to neutral and baseline. These findings add to a small but growing literature indicating possible pupil sensitivity to myriad and interacting influences including cognitive effort, autonomic arousal, motor preparation, and anxiety (Bertrand, Garcia, Viera, Santos, & Bertrand, 2013; Bradley et al., 2008; van Steenbergen & Band, 2013). The relative contributions of these different influences to pupil signal may also vary strongly with psychological context. Neuroimaging methodologies permitting the time-locking of pupil signal to brain activity will be useful in disentangling these relationships.

**Conceptual Implications of Observed Reward/Emotion Effects**

The present findings make it clear that positive emotion and reward manipulations can lead to different effects on cognitive control as indexed by behavioural performance and pupillometric indices, and thus can be dissociated from one another. These
manipulations have been shown to have diverging effects on cognitive control in previous studies, but to our knowledge, no published study has directly compared the effects of these manipulations within a single sample. These results indicate that positive emotion and reward need to be considered distinct when considering their influences on cognition, and further, need to be considered distinct constructs. Investigations in affective neuroscience (e.g., the work of Berridge and others) have provided evidence that hedonic experience of pleasure (i.e., ‘liking’) and goal drive towards rewards (‘wanting’) are neurally distinct but, for the most part, this distinction has not been clearly delineated with regards to influences on cognition. The present study is part of a small but growing literature indicating that this must change.

Another important point that this data reveals, when considered together with previous observations, is that positive affect can have complex and differing effects on cognition. The present data were suggestive of a mild shift towards proactive control, while other, albeit limited, evidence examining the effects of positive affect on cognitive control has been more suggestive of an increase in reactive control and/or cognitive flexibility more generally. Van Wouwe and colleagues (van Wouwe et al., 2009) suggested that inconsistencies between their observations (positive affect increased cognitive flexibility, but did not lower cognitive maintenance) and Dreisbach’s findings (Dreisbach, 2006) could be due to temporal differences in affect manipulations used (tonic versus phasic), but noted that this possibility was not likely; likewise, this possibility is not likely to account for differences between previous data and the present study (which used both tonic and phasic manipulations of positive emotion). Possibilities accounting for differing results of
positive affect in different experimental observations – including differences in task design and/or experienced subjective experience – will need to be explored further.

**Neurobiological Implications of Observed Reward/Emotion Effects**

Present results provide robust evidence that reward incentive manipulations have a larger effect on cognitive control than positive emotion manipulations. This raises the possibility that mechanisms involved in reward motivational processing are more relevant to cognitive control than the mechanisms underlying positive emotion. The neurobiological substrates underlying this pattern of results have yet to be elucidated. Robust evidence has implicated the DA system as a critical component in motivation and reward processing as well as cognitive control, and it has been argued that DA’s involvement in reward-related processing may extend its functional role into the experience of positive affect (Ashby et al., 1999; Wise, 1982). Effects of DA release on PFC are complex, and cognitive effects depend on multiple factors, including temporal dynamics and receptor activity. For instance, phasic DA activity at D1 receptors has been associated with cognitive maintenance, while tonic DA activity at D2 receptors has been associated with cognitive flexibility and updating of representations (Aboitiz, 2009; van Holstein et al., 2011). Thus, it is possible that the differing outcomes that we observed as a result of positive emotion and reward manipulations were both due to dopaminergic activity, but at different dynamics and different receptors. It is possible that differences in dopaminergic dynamics and receptor activity may also account for heterogeneity in observed evidence regarding the effects of positive emotion on cognitive control. However, the role of dopamine in positive emotion has been challenged (i.e., (Berridge & Robinson, 1998) and recent evidence suggests that L-
DOPA, a DA precursor, is not associated with elevated mood (Liggins, Pihl, Benkelfat, & Leyton, 2012). Thus, at present, the neurotransmitter systems underlying positive mood are not yet clear. Given present evidence from the literature, it seems reasonable to speculate that DA influences underlie effects of reward manipulation on cognitive control in the present study, while neurotransmitter influences related to changes in cognition under positive emotion manipulation are not yet clear. This remains a critical area for future investigation.

Consistent with findings from our previous work (Chiew & Braver, 2013), the present data indicates that pupil activity is sensitive to reward and emotional influences, on both tonic and phasic timescales. Given the key role of the locus coeruleus-norepinephrine (LC-NE) system in modulating arousal and pupil dilation, the role of norepinephrine, in addition to dopamine, needs to be examined. Tonic and phasic norepinephrine have been related to differential control states (exploration and exploitation) and indexed by inversely related tonic and phasic pupil activity (Aston-Jones & Cohen, 2005; Gilzenrat et al., 2010; Murphy, Robertson, Balsters, & O’Connell R, 2011). Our data are somewhat consistent with evidence from Gilzenrat and colleagues (2010) that tonic and phasic pupil activity dynamics may be inversely correlated, and that this may occur under both reward and emotion manipulations (given our observation of high phasic/low tonic activity in baseline and neutral block trials, vs. low phasic/high tonic activity in non-incentive trials within the reward block, and in neutral trials within the positive block). Interestingly, adaptive gain theory predicts that a pattern of high tonic/low phasic pupil activity should be predictive of increased task exploration and decreased task engagement. Although the high tonic/low phasic pattern was observed in non-incentive
trials within the reward block, it was associated with a behavioral shift toward enhanced proactive control (i.e., increased task engagement) relative to baseline performance. A similar shift in error rates was associated in neutral trials within the positive block, relative to neutral block performance, although the magnitude of the effect was very small and did not reach statistical significance. Further, incentive trials within the reward block were characterized by high tonic and phasic pupil activity, and were associated with further behavioral shifting toward enhanced proactive control relative to both non-incentive and baseline trials. Positive trials within the positive block were characterized by high tonic but not phasic pupil activity and an increase in proactive control, relative to neutral trials within the positive block; this occurred although pupil activity associated with these different trial conditions did not appear to significantly differ.

Given that adaptive gain theory predicts that low tonic, rather than high tonic, LC-NE activity should characterize motivated performance (i.e., enhanced task engagement), how this pattern of pupil activity might correspond to control state is not yet clear, and may reflect other possible influences (i.e., reward-related dopamine release) on pupil dilation in addition to LC-NE system activity. In contrast, positive trials within the positive block did not show increased phasic pupil activity relative to neutral trials, with correspondingly little behavioural change as a function of trial. Pupil activity in the Emotion session was thus more characteristic of an inverse relation between tonic and phasic pupil activity (and by extrapolation, NE), following that described by Gilzenrat. This raises the interesting possibility that pupil dilation may be sensitive to more complex interactions of multiple neurotransmitter systems. Such an interaction may have been
present with the reward incentive manipulation (i.e., a DA-NE interaction), accounting for a pattern of pupil activity departing from Gilzenrat’s account.

*Aim 1: Experimental Limitations Regarding Observed Reward/Emotion Effects*

While results under reward incentive in the current study were highly consistent with predictions and/or replicated previous data, changes in performance and pupil activity as a result of the positive emotion manipulation were relatively weak, relative to such effects in previous studies where these manipulations were used (e.g., (Dreisbach, 2006; Dreisbach & Goschke, 2004). Several possible limitations may account for these unanticipated results. In the present section, we aim to discuss each of these findings in turn.

First, it is possible that the current data was not analyzed in a way that sufficiently reveals the relationship between positive emotion and performance/pupil outcomes. Regarding task performance, present data analysis is relatively standard for the AX-CPT paradigm, so it is unclear how analysis could be altered to optimally reveal the effect of emotional manipulations. However, analysis of pupillometry data could potentially be improved to help minimize possible noise. Methodology in this area is rapidly developing: the use of pupillometry to study cognition re-emerged relatively recently and, with the development of high-resolution techniques, has been expanding rapidly: a search in MEDLINE\textsuperscript{6} for “pupillometry” and “cognition” revealed 18 citations, 17 of which were published in 2007 or later. While correcting for blinks using a linear interpolation algorithm, as we have done, is relatively standard, other recent studies have begun to use

\textsuperscript{6} Conducted July 9, 2013.
more sophisticated preprocessing techniques (i.e., applying smoothing filters to pupil data to improve the signal to noise ratio; (Nassar et al., 2012). It is possible that investigating and comparing different preprocessing techniques, in this dataset and in other datasets, may result in more reliable and valid pupil data. Refining data processing techniques will be an important direction for future work as pupillometry matures as a research methodology in the service of investigating cognitive psychology and neuroscience questions.

Second, it is possible that the present sample was not engaging in the task, performing the task in a stable manner, or responding to experimental manipulations in a manner typical of the general population investigated (healthy young adults). This possibility seems highly unlikely given the full scale of experimental evidence examined. The sample closely replicated the patterns of performance and pupil activity under reward incentive previously observed in Chiew and Braver (2013), suggesting that participants were capable of performing the AX-CPT paradigm and adjusting performance in response to experimental manipulations within the paradigm. Additionally, analyses of proactive indices suggested that performance did not significantly differ between Baseline and Neutral blocks; thus, no evidence appears present that participants’ baseline performance was significantly different across the Emotion and Reward experimental sessions. Regarding within-task data reliability, time on task analyses suggest that changes in performance over the course of the task were relatively minor and more symptomatic of fatigue than of random instability in performance (the possibility of fatigue is discussed at length in the following section). Formal reliability estimates of behavioural and pupil data were not computed for the present study and, to our knowledge, have not been
characterized for pupillometry investigations of higher cognition. This is an issue that is also common in cognitive neuroimaging studies (reviewed in (Braver et al., 2010), and could be ameliorated by incorporating reliability estimates, such as split-half coefficients across even and odd trials or block sections, into analysis.

The third possibility, likely a more major concern than the prior two in the present dataset, is uncertainty regarding the reliability and validity of the positive emotion manipulations in inducing the intended emotion and effects on cognition. The positive emotion manipulation in the present study was associated with a weak increase in cognitive maintenance, as opposed to increases in cognitive flexibility, which have been reported in previous work (Dreisbach, 2006; Dreisbach & Goschke, 2004). Dreisbach’s previous studies did not include measures from participants (either self-report or psychophysiological measures) on the efficacy of the positive affect manipulations in achieving the desired emotion, making it difficult to directly compare experimental manipulation effects on emotional experience between studies. However, measures assessing emotional experience in the present study suggest that reliability and validity may have been concerns for our emotion manipulation; this may have contributed to our results on cognitive performance and their divergence from previous literature. We will discuss these concerns here.

Self-report of mood valence via the SAM indicated that participants reported a mild increase in mood valence after viewing the positively valenced video, relative to the neutral video (assessment intervals 3 and 4). However, when comparing SAM assessments before and after the positive emotion task block (assessment intervals 4 and 5), self-reported mood valence was lower after the block than before. Similar decreases in mood valence
were observed when comparing SAM assessments before and after the other three task blocks in the study (within the Emotion session, the Neutral block, and within the Reward session, the Baseline and Reward blocks). Mood may have become less positive over the course of each of these task blocks owing to mild fatigue and discomfort over the course of the task block. Each AX-CPT run was ~25 minutes long, and during the run participants were required to sit upright with their head supported by a headrest to minimize motion and maximize pupil signal. To examine the possibility that manipulation effects were attenuated because of fatigue, we analyzed the first third of task runs (first 67 trials out of 200 trials per task run). Results are presented for basic AX-CPT task performance and pupillometry analyses in Table S2 in the Supplementary Material. All experimental effects occurred in the same direction in these analyses of first-third data as in full run data, and overwhelmingly did not change in strength. However, analyses of proactive indices in the Emotion AX-CPT revealed that the increase in proactive control from neutral to positive block, as measured by RT proactive indices, was stronger in the first third of the data than in the full run. Also, when contrasting Reward and Emotion session error proactive indices as a function of block, the main effect of Session (higher proactive indices overall in Reward > Emotion session) reached significance in the first-third data but not in the full run. These findings are bolded in Table S2 in the Supplementary Material and provide some tentative evidence that certain effects may have weakened over time, but do not suggest that this was a major driver of observed effects.

Adding further support for the fatigue account, anecdotal evidence suggested that many participants found it difficult to remain still for the duration of each run, and this may have contributed to decreased mood valence before and after task runs in all conditions.
Time on task analyses also revealed that errors increased over the course of each task block, consistent with the idea that fatigue may have increased over the course of each task block. Accordingly, mood may have declined over the course of each task block, but present study design did not permit for a more fine-grained, ongoing assessment of mood during these periods. Future studies should examine both the possibility of remote eyetracking (without a headrest, facilitating participant comfort – which is key in studies aiming to investigate positive mood effects) and the possibility of a more continuous assessment of mood, either through psychophysiological measures (i.e., facial electromyography for valence, and autonomic activity measures for arousal (P. J. Lang, Greenwald, Bradley, & Hamm, 1993) or through self-report at intervals throughout the task run.

In particular, recent evidence (Schaefer et al., in preparation) suggests that deactivation of corrugator muscles (in the forehead, used when the eyebrows are furrowed in a frown), measured through facial electromyography (EMG), may be a robust and highly reliable index of positive emotional responses; more so than activation of the zygomatic muscle (in the cheeks and active when smiling). Given that online valence of experience has been challenging to reliably measure, this finding provides a promising methodology to be used in the future.

In addition to within-block effects, the SAM data revealed a general decline in mood valence over the course of each experimental session. This decrease in mood may be related to boredom and/or mind-wandering, which may increase over the course of a cognitive task, and tend to be associated with negative thought content (Kane et al., 2007). Because the Positive Emotion block always occurred after the Neutral block (in order to
match experimental design between the Emotion and the Reward session), the combination of this general decline with successful positive mood induction meant that reported mood valences prior to the Neutral and the Positive block were relatively similar \( t(100) = -.913, p = .364 \). In contrast, in the Reward session where no positive emotion induction took place, reported mood valence prior to the Baseline block was higher than mood valence prior to the Reward block \( t(96) = 2.365, p = .02 \). Such gradual declines in mood, possibly related to boredom/mind-wandering, are a likely occurrence in numerous studies investigating affect/reward influences on cognition, but are not always assessed.

Judging from the results of the present study’s SAM assessments, self-reported decline in mood valence over the course of an experimental session can reach statistical significance and may interact with experimental manipulations intended to induct particular moods or emotions. Counterbalancing the order of emotion induction administration and tighter experimental control of experience sampling (i.e., using assessment tools from the mind-wandering literature) may help in addressing these concerns. As it stands, evidence from the present data suggest that fatigue and mind wandering may have interacted with the positive emotion manipulation, making it less effective in achieving its desired effect on cognitive performance. At this time, this possibility remains to be clarified by future research: effect sizes of positive emotion effects on cognition have generally not been reported in previous data and remain relatively unknown: accordingly, influences of fatigue or mind-wandering in attenuating these effects also remain uncharacterized. Effect sizes of significant emotion effects on performance and pupil activity in the present study (as shown in Tables 10-12) range from \( \eta^2 = 0.002\text{-}0.07 \); i.e., small-to-medium effects (J. Cohen, 1988). Given that these effect sizes did not appear to
substantially change when examining the early part of the task run, presumably where fatigue effects would be weakest, it may be that fatigue is not a major factor in changing emotional effects on cognition over time, but this issue requires much more systematic examination than that available in the present investigation to definitively clarify.

Another important consideration is whether the trial-by-trial manipulation of affect, via presentation of IAPS pictures was effective or not. Indeed, our available evidence suggests that the IAPS pictures may not have had the intended effect. Specifically, we conducted an IAPS passive viewing run to provide an assessment (via pupil dilation) of the emotional arousal elicited by the IAPS images, independent of task-evoked changes in pupillary activity. This run followed the general rationale and timing of the protocol used by Bradley and colleagues (Bradley et al., 2008), which was used to demonstrate that viewing of emotionally evocative stimuli was associated with increased pupil dilation and autonomic arousal, relative to viewing of neutral stimuli. Pupil data from the present study did not replicate Bradley's finding of greater pupil dilation during viewing of emotional images compared to neutral images. Intriguingly, pupil dilation differentiated as a function of the images' old/new status: pupil dilation during viewing was greater for images previously viewed (i.e., included in the AX-CPT runs) than for new images, a finding consistent with studies investigating pupil activity associated with recognition memory (Otero et al., 2011). While the passive viewing run was not designed explicitly to test for old/new effects, the combined presence of the old/new effect and the absence of the emotion valence effect are intriguing because they validate that pupil signal in the passive viewing run was responsive to psychological influences, while at the same time indicating
that the IAPS pictures viewed did not actually elicit the desired emotion (and related arousal).

It is important to note that the IAPS images presented in the current study were selected to follow Dreisbach (2006), where presentation of positively valenced IAPS images on a trial-by-trial basis was found to be associated with decreased maintenance and greater flexibility in AX-CPT performance relative to neutral. Our failure to replicate such effects suggests the possibility that these IAPS stimuli may not reliably elicit emotional arousal, which in turn raises important questions for the emotion literature. Unfortunately, neither the present study nor Dreisbach’s study elicited self-reported valence and arousal ratings for the presented IAPS stimuli from their experimental samples; according to IAPS norms, the images used as positive and neutral stimuli should be appropriately evocative, but this cannot be independently verified via overt report in either sample.

If it was in fact the case that the emotional stimuli shown in the present study did not elicit emotional arousal (which should be directly rated, along with valence, by participants in follow-up investigations), then we must question what else could lead to trial-based differences in task performance between neutral and positive emotion trials (even though these were statistically modest and only present in RT), given that they were randomly intermixed within the Positive Emotion block and only differentiated by the valence of the IAPS picture presented. No changes in pupil activity were observed during cue maintenance as a function of trial-based emotion condition, providing convergent evidence that changes in emotional arousal did not drive the observed performance changes. It may be possible that our failure to replicate Bradley et al. (2008) was due to the design of our IAPS passive viewing run. One key difference between our IAPS passive
viewing run and the protocol used by Bradley and colleagues is that our viewing run included only positively and neutrally-valenced images, while the Bradley protocol used positive, neutral, and negative images. It is possible that the presence of negative images create a context where greater variation in the emotional valence elicited by stimuli is present, and thus psychophysiological responses to differently valenced images are relatively accentuated. Follow-up studies could use a design with images from all three emotional valence categories to clarify whether matching contextual effects leads to a closer replication of the results observed by Bradley et al. (2008).

Another possibility worth considering is that the design of the present paradigm more generally may have been suboptimal to address the experimental questions at hand. We will address each of the aspects of the present design that may have obscured the intended results in turn. A first concern is the use of a within-subjects design in the present study, as opposed to a between-subjects design. While examining the effects of positive emotion (neutral versus positive emotion) and reward (baseline versus reward) manipulations within a single sample was desirable, particularly when considering the influences of individual differences, it may be that subjecting participants to both manipulations may have altered the nature of the manipulations. While session order was counterbalanced in an effort to control for the effect of subjecting participants to both positive emotion and reward manipulations, each experimental session involved task performance under two different inductions (neutral/positive or baseline/reward). In particular, in the Emotion session, the positive emotion block was always performed following the neutral block, while previous studies of positive emotion on cognitive control (e.g., (Dreisbach, 2006; van Wouwe et al., 2009) used a between-subjects design where participants only performed
the cognitive task under a single affect induction. Combining multiple emotion inductions within a single experimental session could have led to carryover or mixture effects.

Second, timing of the present paradigm design could have been suboptimal for inducing the desired induction effects. Our AX-CPT paradigm used a relatively long ITI (4000ms), in order to allow the pupil signal to return to relative rest prior to the start of a new trial. Previous studies examining influences of positive affect on cognitive control have used shorter ITIs (1250 ms in Dreisbach, 2006; 1200ms in Van Wouwe et al., 2009); it is possible that positive emotion induction effects may operate within a critical window of time, and longer ITIs could have diluted their effects. Such concerns are somewhat mitigated with regard to reward incentive effects: we conducted a previous study limited to examining incentive manipulations on AX-CPT performance using two different ITIs (Chiew & Braver, 2013) and observed that differing ITIs generally did not affect performance or pupil effects as a result of incentive. However, no such systematic comparison exists regarding design timing under positive emotion induction.

Finally, it is important to note that very little consensus or knowledge of replication exists regarding task paradigms to probe interactions of emotion and cognitive control. Using the AX-CPT seemed logical given our predictions regarding proactive versus reactive control and its use in previous studies of positive emotion and cognitive control (Dreisbach, 2006; van Wouwe et al., 2009). However, it remains that the effects of positive emotion on cognition have been investigated with a wide array of tasks, including creative problem-solving tasks (Isen et al., 1987), global-local processing tasks (Fredrickson & Branigan, 2005), and attentional/cognitive control tasks (Dreisbach & Goschke, 2004; Rowe et al., 2007). Nevertheless, tests for replication of these effects are rarely conducted, and there
are still only a few studies that have examined positive emotion effects specifically on the AX-CPT. Thus, the generalizability of previous experimental findings across task paradigms remains uncertain, especially given that the effects of positive affect on cognition may depend on specific experimental factors. For example, Kuhl and Kazen (Kuhl & Kazen, 1999) observed that positive affect reduced Stroop interference, but only when generated in conjunction with the generation of a difficult intention/action plan representation in working memory. Whether the effects of positive affect in other cognitive control paradigms such as the AX-CPT depend on similar higher-order interactions, intentionally or unintentionally part of the task design, remains to be investigated.

Aim 2: Examining Individual Differences in Relation to Performance and Pupil Activity

The second aim of the present study was to relate changes in task performance and pupil activity to stable individual differences. Thus, the study utilized a large sample, and individual differences in personality traits thought to relate to reward versus punishment sensitivity, and positive versus negative affect, were collected and examined. Individual measures of working memory capacity and trait anxiety were also collected and analyzed to test for a relationship to task performance and pupil activity.

Factor analysis revealed that personality traits loaded onto four factors: one factor associated with positive affect and reward sensitivity, one factor associated with Extraversion and general incentive sensitivity (to both rewards and punishments), one factor associated with negative affect, and one factor associated with punishment sensitivity. This factor structure differed from that observed in Locke and Braver (Locke & Braver, 2008), where individual differences loaded onto two factors (related to reward
sensitivity and punishment sensitivity). Individual differences Hypothesis 1 predicted that individual differences in reward sensitivity measures would be correlated with the extent to which proactive control and preparatory pupil dilation increased under incentive. Contrary to this hypothesis and previous evidence that reward sensitivity may be related to incentive-related changes in cognitive performance or physiological measures (i.e., Engelmann, Damaraju, Padmala, & Pessoa, 2009; Jimura et al., 2010; Padmala & Pessoa, 2011), neither reward-related factor significantly correlated with reward rates, raw measures of performance under incentive or increases in proactive control under incentive. There were some suggestions that reward sensitivity may correlate with pupil dilation at cue maintenance (i.e., preparatory activity) in non-incentive A-cue trials. Given the absence of significant relationships between reward sensitivity and overt performance, it may be possible that the significant correlations observed may have reflected arousal-related, rather than cognition-related, changes in pupil dilation as a result of reward, which were greater in highly reward-sensitive individuals. This possibility remains preliminary, especially given present limitations on separating cognitive and affective influences on pupil signal, and remains to be clarified by future research.

Analyses from individual differences Hypothesis 2, which examined the relationship between personality, performance, and self-reported changes in mood in response to positive emotion induction, helped provide a more complete picture of effects in the data. Hypothesis 2 analyses revealed that individual differences in positive emotion/reward sensitivity, as indexed by Factor 1, were positively correlated with self-reported increases in mood arousal in response to positive emotion induction. This finding helps serve as a check of construct validity: that individual difference measures relating to positive
emotion/reward relate to the extent to which participants experienced positive emotion in response to the induction.

Individual differences Hypothesis 3 predicted that working memory capacity (WMC; measured via the O-span) would be positively correlated with proactive control and sustained pupil activity (i.e., a measure of mental effort). This was not the case. WMC significantly correlated with faster RTs in the baseline block, but not specifically with increased proactive control. No significant correlations between WMC and pupil activity were observed. This does not replicate results by Heitz and colleagues (Heitz et al., 2008), who reported greater pupil dilation in individuals with higher WMC. However, Heitz and colleagues used pre-selected groups of high and low WMC individuals in their investigation – because we did not pre-select participants on the basis of WMC in the present study, it may be possible that inadequate variance was present to support a significant correlation.

Individual differences Hypothesis 4 predicted that trait anxiety would be negatively correlated with proactive control in task performance, given predictions from the cognitive efficiency hypothesis that worrying consumes cognitive resources that could otherwise be engaged by proactive cognitive control (more efficient, but also more demanding than reactive control). This prediction was also not supported by the present data. Given current literature, both increased and decreased pupil activity could be expected to be observed in relation to increased trait anxiety, given evidence that anxiety is associated with increased pupil dilation during the pain response (Bertrand et al., 2013) but also predictions from the cognitive efficiency hypothesis, which might suggest that higher anxiety is associated with lower resource availability and decreased proactive control, and therefore with lower pupil dilation (Fales et al., 2008).
It is also possible that both kinds of effects (increased and decreased pupil dilation) could have been present in the present data, canceling each other out, and thus contributing to the observed null association between anxiety and pupil dilation. Following up these findings with investigations to clarify the influence of anxiety on the pupil response is an important future research direction. Additionally, research making use of pupillometry to track the dynamics of pain (as in the Bertrand study) has yet to be bridged with research using pupillometry to track dynamics of cognition: this is an exciting future subject area to explore, building on neuroimaging research exploring common neural circuitry and interactions between cognitive processing and the experience of pain (Atlas, Bolger, Lindquist, & Wager, 2010; Atlas & Wager; Buhle et al., 2012).

**Aim 2: Experimental Limitations Regarding Observed Effects of Individual Differences**

Despite previous evidence suggesting predictive relationships between individual difference measures and cognitive performance, significant correlations between such measures and performance/pupil activity were elusive in the present study. As previously done for observations regarding the current study’s first aim, we examine possibilities that could account for the null findings in the individual differences analyses.

The first possibility is that data quality/analysis may have obscured relationships between individual difference measures and performance/pupil outcomes. Given that correlations may be more sensitive to noise in the data than analyses of main effects (Yarkoni & Braver, 2010), data quality issues are paramount for these analyses, particularly correlations between individual difference measures and pupil activity. Many of the potential concerns regarding pupillometry data processing were discussed under
Aim 1. Additionally, however, significant relationships between targeted variables may have been obscured by influences from extraneous (i.e., confounding, suppressor) variables, which is always a potential concern for correlation / regression analyses. Candidate extraneous variables could be considered and controlled for in further analyses of the present data. For example, we did not observe a significant correlation between working memory capacity and proactive control in the present study. While controlling for non-specific differences in performance (i.e., controlling for BY performance) did not replicate Richmond et al.'s findings of a significant relationship between WMC and proactive control, the possibility that uncontrolled variables could obscure significant relationships should be generally taken into account in future investigations.

The second series of possibilities is that the present sample did not display individual differences within norms for the population intended (healthy young adults), that the individual differences investigated were subject to measurement error or reliability problems. The current sample's means and standard deviations on individual difference measures are listed in Table 2, along with published values from normative samples (where available). In the current sample, the individual difference measures were closely in line with published norms for the most part. However, one exception was the NEO Five Factor Inventory. Our participants scored higher than norms on all five factors. Given scores in the normative range in other individual differences, the reasons for these elevated scores are unclear. One point to keep in mind is that the norms reported by McCrae and Costa (2004) are taken from two samples: high school students (ages 14-18) and a lifespan community sample (ages 19-93); it is possible that college students, especially from a highly selective institution like Washington University, may present with
a slightly different personality profile than a community sample. This may have led to a slightly different profile of reward sensitivity than typical of the general population, contributing to the null findings observed when correlating reward sensitivity with performance measures. However, given that previous studies from our laboratory reporting influences of individual differences on motivation-cognitive control interactions (i.e., Jimura et al., 2010; Locke and Braver, 2008) used very similar samples drawn from the same university population, failure to replicate those previous results as a result of the sample seems unlikely.

It is also possible, although unlikely, that the individual difference and task measures studied were subject to measurement error and/or reliability problems. While we will not recap the data here, each questionnaire used was tested for reliability in development and found to be acceptable; psychometric properties are listed in the citations for each questionnaire. Measurement error is a possibility, given that participants completed the questionnaires at home between experimental sessions and did not have immediate opportunity to ask the experimenter to clarify questionnaire directions, if any clarifications were needed. However, the present questionnaires have been widely used and ambiguity in completion, especially given the present sample of healthy young adults, seems unlikely. The AX-CPT paradigm has also been recently examined for test-retest reliability across two time intervals (i.e., three testing sessions) and was found to show an intraclass correlation coefficient (ICC) of 0.69 (Strauss et al., in press). This is just below the threshold of ICC = 0.70 suggested for clinical trial use, but still suggests that the AX-CPT achieves a robust level of reliability and reliability problems with this paradigm in the present study were unlikely.
A third possibility is that the individual differences measured did not have adequate construct validity in relation to the emotion/reward experimental manipulation effects observed. Previous evidence has suggested that individual differences in reward sensitivity predict the extent to which reward incentives modify cognitive performance (i.e., Locke and Braver, 2008; Jimura et al., 2010), but those observed relationships occurred in smaller samples than the present sample and may not adequately reflect the general population, accounting for an insignificant effect in our conceptual replication. Additionally, whether stable individual differences in reward sensitivity correlated with the efficacy of the positive emotion manipulation was largely an exploratory hypothesis. This hypothesis was upheld in self-reported arousal data, but not in valence data. Recent evidence suggests that Extraverts are more prone to positive affect than introverts owing to heightened reward responsivity (Smillie et al., 2012), but introvert/Extravert differences in positive affect disappear in pleasant (but non-appetitive) situations. Our positive emotion manipulation was intended to induce positive but non-appetitive emotion, relative to the reward manipulation, and this may have accounted for the fact that it did not relate more closely to the Positive Affect / Reward Sensitivity factor that emerged from the personality data.

Finally, as discussed previously regarding Aim 1 data, contributions to variance in the pupil signal are not currently well-understood. Thus, null results in correlations between individual differences and pupil activity measures could indicate that these measures tap different constructs, or it is possible that noise in the pupil data could be obscuring significant relationships. Future work is required to probe this question further.

Questions for Future Research
While we have alluded to several points of clarification for future research in the present discussion of experimental results and limitations, these clarifications point to higher-level questions that the study of emotion, motivation and cognition must address. These key questions include the following: (1) What accounts for cross-study variation in the observed effects that positive emotion has on cognitive control? (2) Does similar variation exist in the effects of reward motivation on cognitive control? (3) What are the neurobiological mechanisms that underlie the diversity of these effects? (4) How does subjective hedonic experience compare under positive emotion, compared to reward motivation manipulations? (5) What is the best way to monitor such hedonic experience on an ongoing basis? And a last key question, raised by the results of the present study but not directly related to the study of emotion, motivation and cognition: (6) What are the cognitive and affective influences to which pupil dilation is sensitive, and how can we best interpret the dynamics of pupil signal to understand these influences?

Follow-up studies need to explore these questions. Questions 1 and 2 are challenging to address, but could be tackled by systematic manipulation of task design and emotion/reward induction. For example, future studies could examine whether there are critical task, design, or person determinants by which positive emotion may lead to enhanced flexibility or not. Likewise, maybe there are similar manipulations that determine whether reward motivation leads to enhanced proactive control, or if under some situations it can lead to reactive control/greater flexibility instead (i.e., in a rewarded AX-CPT paradigm, by providing higher payoffs for successful AY performance than BX performance). Question 3 could be addressed by combining such design manipulations
with methodologies such as neuroimaging and pharmacological manipulations that alter DA activity, such as L-DOPA administration.

In contrast, Question 4 and 5, regarding subjective hedonic experience, are central questions not only in investigations of emotion/motivation-cognition interactions but for the more general field of emotion science. Psychophysiological markers such as corrugator muscle deactivation as measured by facial EMG (Schaefer et al., unpublished) show promise as probes of ongoing valenced experience, and may be combined with neuroimaging methods to elucidate the neural mechanisms underlying such experience (Heller, Greischar, Honor, Anderle, & Davidson, 2011).

Lastly, Question 6, regarding the nature of the pupil signal, may be informed by single-trial analyses of data involving cognitive and emotion/reward processing, including the present dataset. For example, an examination of the extent to which pupil dilation on each trial can be predicted by emotion or incentive condition, by RT, or by such factors in interaction with one another, may help characterize how much the pupil signal reflects cognitive effort (at least in terms of overt performance) as opposed to nonspecific arousal influences (elicited by emotion or reward manipulation).

General Conclusions

Overall, results in the present study showed complex patterns in response to positive emotion and reward manipulations, some of which replicated previous experimental observations and some of which did not. While task performance and pupillometry results under reward incentive were consistent with the idea that reward incentives promote proactive control, performance and pupil activity under positive
emotion showed a dissociable, more complex pattern generally characterized by a weak shift towards proactive control. Small proactive shifts appeared to occur on both a block-based and trial-based level, but when the effects were compared directly against the reward condition, using proactive index calculations, they were found to be significantly weaker. Thus, we are hesitant to interpret this increase in proactive control as positive emotion-related in nature. In general the differential nature and magnitude of the effects under reward incentive and emotion suggest that these constructs are distinct in nature and can be dissociated from one another in terms of their influences on cognitive control.

The present study and its limitations highlight the complexity and challenges of inducing positive emotion in the lab in an ecologically valid manner and sustaining it over time in order to examine its effects on cognition. Inducing and examining the effects of reward induction was relatively straightforward; reward effects were robust, closely replicated previous results, and were logical to interpret. In contrast, by nature the validity of the positive emotion induction is defined by subjective experience, which is more difficult to characterize than reward incentives. While we used positive emotion inductions from previous studies (i.e., (Dreisbach, 2006; Gray, 2001) that appeared to successfully induce the desired emotion and lead to interpretable effects upon cognition, the performance and pupil data that we observed under positive emotion was not nearly so interpretable.

In particular, it remains unclear from the SAM assessments whether participants experienced emotion in response to the induction to an extent replicating previous research. While the emotion induction of the present study appeared to be successful and yield results on performance that are distinct from those under reward manipulation,
addressing our central question regarding the dissociability of these constructs, our understanding of emotion and motivational influences on cognition is still at an early stage.

A key finding emerging from multiple analyses in the present study is the fact that pupil dilation cannot be explained as an indicator of mental effort alone. Findings in the present data, including observations that pupil dilation was associated with experimental emotional manipulations in the absence of large overt behavioural changes, and associated with faster RTs but not with superior cognitive control, build on a small but growing literature indicating possible pupil sensitivity to influences beyond cognitive effort, including autonomic arousal, motor preparation, and anxiety (Bertrand et al., 2013; Bradley et al., 2008; van Steenbergen & Band, 2013). The relative contributions of these different influences to pupil signal may also vary strongly with psychological context.

Given the uncertain nature of the pupil signal, more work will be needed to clarify the mechanisms underlying its activity, and whether individual variability in the contributions these mechanisms make to pupil signal can be characterized and related to other stable individual differences. One could imagine variability in so-called “reward efficiency”, the extent to which responses to rewards (themselves influenced by stable differences in reward sensitivity) lead to changes in incentive-driven cognition and behaviour. Whether such variability can be characterized has yet to be determined, although the possibility has been alluded to in previous investigations of motivation-cognition interactions (Locke and Braver, 2008). Neuroimaging methodologies relating pupil signal to brain activity more explicitly will be key to clarifying sources of variability in the pupil signal.
Such methodology will also be important in elucidating the neurobiological mechanisms underlying these effects. Previous literature provides robust evidence for dopamine influences in reward processing, although debate remains regarding the role of dopamine (DA) in positive emotion. Meanwhile, pupil dilation has been strongly linked to activity in the norepinephrine system: changing pupil dynamics as a result of emotion and reward manipulations on cognition provide peripheral evidence that both norepinephrine and dopamine systems may be involved in these interactions.

While a major aim of the present study had been to investigate the influences of stable individual differences on emotion/motivation-cognition interactions in task performance and pupillometry, many of the analyses relating individual differences and performance/pupil measures did not reach significance as anticipated. A number of possible factors could have contributed to these null results. Even though a number of the hypotheses tested in the current study were based on significant findings in previous research, it is possible that this may be due to an under-reporting of null effects in previous literature (i.e., the ‘file-drawer’ problem; (Rotton, Foos, Van Meek, & Levitt, 1995), which may make the relationships seem more robust than they actually are. Indeed, concerns about problems with replicability and reliability have recently been receiving increased attention and scrutiny within both psychological (Carpenter, 2012; Makel, Plucker, & Hegarty, 2012; Pashler & Wagenmakers, 2012; Simmons, Nelson, & Simonsohn, 2012) and cognitive neuroscience research (Aron, Gluck, & Poldrack, 2006; Carp, 2012; Congdon et al., 2012; Yarkoni, 2009; Yarkoni & Braver, 2010). As a related point, various influences may have acted as noise in the present dataset, masking significant correlations between experimental factors. For example, as discussed previously, fatigue or boredom from
participating in multiple task blocks per session may have weakened the strength of the positive emotion manipulation. Individual difference correlations using pupil effects also may have been susceptible to noise in the pupil data.

In sum, results from the present study indicate that both positive emotion and reward incentive manipulations may affect cognitive control, and that while there may be both similarities and differences in the results of these manipulations, evidence generally suggests that these influences are distinct from one another, supporting an account where positive emotion and reward motivation can be dissociated from one another. Incentive manipulations led to increased proactive control, as anticipated, but positive emotion led to a more complex pattern that did not replicate previous experimental findings. Several of the hypotheses that we entered the current study with were not supported by the data. Future research to better characterize these relationships may help clarify why several hypotheses based on previous experimental observations failed to replicate. Many directions for such future research have been suggested here and will provide possible avenues by which these complexities can be explored and characterized, continuing progress in bringing research in affect-cognition interactions to the level of understanding current in other cognitive domains.

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Supplementary Material

Analyses Examining Emotion AX-CPT Task Performance and Pupil Activity in Participants

Demonstrating Positive > Neutral Pupil Dilation During IAPS Passive Viewing Run (N=35)

While pupil dilation during passive viewing of IAPS images was not significantly greater for positive images compared to neutral images (and pupil dilation during viewing was numerically Neutral > Positive for the full sample), a subsample of participants (N=35 of N=89 with passive viewing data) did show numerically greater Positive > Neutral pupil activity, as hypothesized. Given that a pattern of Positive > Neutral pupil dilation during passive viewing of IAPS images was consistent with greater emotional arousal in response to positive versus neutral pictures, it is possible that participants showing this pattern may have also demonstrated larger effects of the positive emotion manipulation on task performance and pupil activity in the AX-CPT. We thus conducted analyses on task performance and pupil activity in the Emotion AX-CPT in this subsample and compared them to the same analyses conducted in our full sample. Comparisons are presented in Table S1. These analyses suggest that the effects of the positive emotion manipulation on task performance and pupil activity were relatively similar in individuals who experienced Pos > Neut pupil dilation when passively viewing IAPS images, and those who did not.
Table S1. Comparison between Emotion AX-CPT task performance and pupil activity in individuals who showed Positive > Neutral pupil dilation during the IAPS passive viewing run (N=35) and the full sample (who demonstrated Neutral > Positive pupil dilation as a group; difference was not statistically significant). Significant ($p < .05$) results listed, along with effect sizes.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Effect in subsample with Pos &gt; Neut pupil activity during passive viewing of IAPS images (N=35; with effect size)</th>
<th>Effect in full sample</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Task Performance:</strong> Block-Based Effects in Emotion AX-CPT (error rates)</td>
<td>Cue (A&gt;B; $\eta^2 = 0.038$) Probe (Y&gt;X; $\eta^2 = 0.056$) Block x Cue (A&gt;B more in POS; $\eta^2 = 0.034$) Cue x Probe (AY &gt; others; $\eta^2 = 0.127$)</td>
<td>Block (trend; NEUT &gt; POS; $\eta^2 = 0.005$) Cue (A&gt;B; $\eta^2 = 0.071$) Probe (Y&gt;X; $\eta^2 = 0.09$) Block x Cue (A&gt;B more in POS; $\eta^2 = 0.016$) Block x Probe (Y&gt;X more in POS; $\eta^2 = 0.068$) Cue x Probe (AY &gt; others; $\eta^2 = 0.159$)</td>
</tr>
<tr>
<td><strong>Task Performance:</strong> Block-Based Effects in Emotion AX-CPT (RTs)</td>
<td>Cue (A&gt;B; $\eta^2 = 0.4507$) Probe (Y&gt;X; $\eta^2 = 0.249$) Cue x Probe (AY &gt; others; $\eta^2 = 0.230$)</td>
<td>Cue (A&gt;B; $\eta^2 &gt; 0.496$) Probe (Y&gt;X; $\eta^2 = 0.289$) Cue x Probe (AY &gt; others; $\eta^2 = 0.278$)</td>
</tr>
<tr>
<td><strong>Task Performance:</strong> Trial-Based Effects in Emotion AX-CPT (error rates)</td>
<td>Cue (A&gt;B; $\eta^2 = 0.092$) Probe (Y&gt;X; $\eta^2 = 0.090$) Cue x Probe (AY &gt; others; $\eta^2 = 0.116$)</td>
<td>Block (trend; NEUT &gt; POS; $\eta^2 = 0.005$) Cue (A&gt;B; $\eta^2 = 0.071$) Probe (Y&gt;X; $\eta^2 = 0.09$) Block x Cue (A&gt;B more in POS; $\eta^2 = 0.016$) Block x Probe (Y&gt;X more in POS; $\eta^2 = 0.068$) Cue x Probe (AY &gt; others; $\eta^2 = 0.159$)</td>
</tr>
<tr>
<td><strong>Task Performance:</strong> Trial-Based Effects in Emotion AX-CPT (RTs)</td>
<td>Cue (A&gt;B; $\eta^2 = 0.491$) Probe (Y&gt;X; $\eta^2 = 0.274$) Cue x Probe (AY &gt; others; $\eta^2 = 0.248$)</td>
<td>Emotion (trend POS &gt; NEUT; $\eta^2 = 0.002$) Cue (A&gt;B; $\eta^2 = 0.527$) Probe (Y&gt;X; $\eta^2 = 0.312$) Emotion x Cue (faster B trials in POS; $\eta^2 = 0.002$) Cue x Probe (AY &gt; others; $\eta^2 = 0.298$)</td>
</tr>
<tr>
<td>Pupil Activity: Block-Based Effects in Emotion Session</td>
<td>Sig (Pos &gt; Neut; $\eta^2 = 0.009$)</td>
<td>Sig (Pos &gt; Neut; $\eta^2 = 0.007$)</td>
</tr>
<tr>
<td>Pupil Activity: Trial-Based Effects in Emotion Session</td>
<td>Cue (B&gt;A; $\eta^2 = 0.015$)</td>
<td>Cue (B&gt;A; $\eta^2 = 0.009$)</td>
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</tbody>
</table>

**Exploratory Analyses Relating Individual Differences in Reward/Punishment Sensitivity (Average Composite Measures) to Task Performance and Pupil Activity**

The primary hypothesis related to these stable individual differences was that reward sensitivity would be positively correlated with increased proactive control and increased preparatory pupil dilation under incentive. Analyses in the present
supplementary section examine relationships between reward sensitivity and
performance/pupil activity in the Emotion session, and relationships between punishment
sensitivity and performance/pupil activity in both experimental sessions. We did not have
strong a priori hypotheses about these relationships; hence they are considered
exploratory in nature.

As well as a reward sensitivity composite measure averaged from BAS, GRAPES-
REW and RFQ-promotion, we calculated a punishment sensitivity composite measure
averaged from BIS, GRAPES-PUN, and RFQ-prevention. Like the reward sensitivity
composite measure, the punishment sensitivity composite measure did not significantly
correlate with reward rates, raw error rates or RTs in the Reward block.

Correlating the reward sensitivity and punishment sensitivity measures with task
performance measures in the Emotion session (about which we had no prior hypotheses)
revealed the following: a significant negative correlation between reward sensitivity and
the proactive index (in RTs) on positively valenced trials within the positive block \( r(97) = -.228, p = .025 \); a significant negative correlation between punishment sensitivity and the
proactive index (in error rates) on positively valenced trials in the positive block \( r(98) = -.311, p = .002 \). The punishment sensitivity measure was also negatively correlated with the
proactive index (in RTs) on baseline block trials \( r(98) = -.313, p = .002 \) and neutral block
trials \( r(97) = -.210, p = .039 \). These patterns suggest that reward sensitivity predicted the
extent to which participants tended towards proactive performance specifically in
positively valenced trials, and with a negative correlation (i.e., higher reward sensitivity
was correlated with less proactive control under positive emotion). Further, present
results suggest that punishment sensitivity might be negatively correlated with proactive
control under neutral/baseline and positive emotion conditions, in the absence of incentive manipulations. However, these results should be treated with caution, given that they were not anticipated and likely would not survive multiple comparisons correction.

We had an a priori hypothesis that reward sensitivity might be positively correlated with greater pupil dilation, reflecting greater cognitive effort, at cue maintenance under incentive (as described in the main text), but also conducted exploratory analyses correlating reward and punishment sensitivity measures with pupil activity in the Emotion session, and in both the Reward and Emotion sessions at the pretrial period (which we did not anticipate to directly reflect preparatory mental effort as much as pupil activity during cue maintenance). These exploratory analyses revealed significant correlations between Reward Sensitivity and pupil activity at cue maintenance for neutral A-cue trials within the positive emotion block \( [r(85) = .246, p = .023] \), and positive A-cue trials \( [r(85) = .232, p = .033] \). No other significant correlations between reward or punishment sensitivity and pupil magnitude at cue maintenance or during the pretrial period were observed. Given their exploratory nature, these correlations need to be treated with caution.

*Exploratory Analyses Relating Individual Differences in Reward/Punishment Sensitivity (Average Composite Measures) to Task Performance and Pupil Activity*

As described in the main text, factor analysis on reward and punishment-related stable individual differences revealed a four-component solution, where the first two factors related to aspects of reward sensitivity (Pos Affect/Reward Sensitivity and Extraversion/BISBAS), and the third and fourth factor related to aspects of punishment sensitivity (negative affect and punishment processing, respectively). We had a priori
hypotheses that reward sensitivity would be positively correlated with increased proactive control and increased preparatory pupil dilation, which were discussed in the main text.

As was done using averaged composite measures of reward and punishment sensitivity, analyses in the present supplementary section examine relationships between the two reward sensitivity factors and performance/pupil activity in the Emotion session, and relationships between the third and fourth (Negative Affect and Punishment Processing) factors and performance/pupil activity in both experimental sessions. We did not have strong a priori hypotheses about these relationships; hence they are considered exploratory in nature.

The first factor, Positive Affect/Reward Sensitivity, did not significantly correlate with any task performance or pupil measures in the Emotion session. The second factor, Extraversion/BISBAS, was significantly negatively correlated with proactive index measures in the Positive trials, both for errors \([r(81) = -.233, p = .037]\) and for RTs \([r(82) = -.264, p = .018]\). This correlation suggests that the higher participants measured on the second factor, reflecting Extraversion and both BIS/BAS sensitivity, the less proactive they were in Positive trials, but given the exploratory nature of this correlation, it should be taken with reservation.

The factor loading of the third factor (i.e., the Negative Affect factor) was not significantly correlated with any task performance measures. When correlated with pupil activity measures, a trend-level positive correlation was observed with Incentive—Non-Incentive pupil dilation at cue maintenance in B-cue trials \([r(80) = .208, p = .064]\). This correlation suggests that the higher participants measure on the third factor, reflecting
negative affect, the greater their pupil dilation with incentive relative to non-incentive. It should be noted that this result is not that robust, given it only reached a trend level.

When correlated with task performance measures, the factor loading of the fourth factor (i.e., the Punishment Sensitivity factor) was found to be significantly negatively correlated with global error rates in the Positive block [$r(82) = -.226, p = .042$]. When correlated with pupil activity measures, correlations only reached significance with the Punishment Sensitivity factor during maintenance for trials in the Positive block, but these correlations were positive and significant for all four conditions examined: neutral A-cue trials in the positive block [$r(76) = .231, p = .044$], neutral B-cue trials in the positive block [$r(76) = .231, p = .045$], positive A-cue trials [$r(76) = .226, p = .049$], and positive B-cue trials [$r(76) = .269, p = .018$].

**Exploratory Analyses Relating Individual Differences in Trait Anxiety to Pupil Activity**

These analyses, examining the relation between trait anxiety and pupil activity, supplement analyses in the main text testing the hypothesis that trait anxiety, measured via the STAI, would be negatively correlated with proactive control in task performance measures. To our knowledge, no evidence currently exists regarding the relationship between anxiety and pupillometric activity during performance of a cognitive task. Differing tentative hypotheses regarding the relationship between anxiety and pupil activity may be proposed: given pupil dilation’s status as a putative measure of cognitive effort, higher trait anxiety may be negatively correlated with task-related pupil dilation. However, given recent evidence suggests that anxiety may be associated with increased pupil dilation during the experience of pain (Bertrand et al., 2013), it could also be
hypothesized that trait anxiety and pupil dilation may be positively correlated. We correlated pupil activity both at the pretrial period and during cue maintenance, for both the Emotion and Reward sessions, with the Trait Anxiety measure. However, no significant correlations between Trait Anxiety and pupil activity were observed at either of these periods (all p-values > .232).

Analyses Examining Performance and Pupil Activity in the First Third of Task Run versus Full Task Run

As referenced in the Discussion section of the main text, fatigue and boredom factors may have attenuated the effects of our experimental manipulations, particularly the positive emotion manipulation, leading to weak effects on cognitive performance. To investigate this possibility, we examined task performance and pupil activity in the first third of each task run (first 67 trials) versus in the full run (200 trials in total). The outcomes of these analyses are compared in Table S2. Effects of interest are bolded and discussed in the Discussion section of the main text.
**Table S2.** Comparisons of task performance and pupil analyses in the AX-CPT in the first third of the task runs (first 67 trials, out of 200 in each task run) versus in the full task run (200 trials), to examine for the possibility that fatigue attenuated experimental manipulation effects.

<table>
<thead>
<tr>
<th>Session</th>
<th>Effect Examined</th>
<th>Analysis</th>
<th>Effects in First 1/3 of Task Run</th>
<th>Effects in Full Task Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reward AX-CPT</td>
<td>Block-Based Effects on Task Performance: Errors</td>
<td>Block (Baseline, Reward) x Cue (A,B) x Probe (X,Y)</td>
<td>Block ($p = .294$)</td>
<td>Block ($p = .031$)</td>
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<tr>
<td>Reward AX-CPT</td>
<td>Block-Based Effects on Task Performance: RTs</td>
<td>Block (Baseline, Reward) x Cue (A,B) x Probe (X,Y)</td>
<td>Block ($p &lt; .001$)</td>
<td>Block ($p &lt; .001$)</td>
</tr>
<tr>
<td>Reward AX-CPT</td>
<td>Block-Based Effects on Task Performance: Proactive Indices (Errors and RTs)</td>
<td>Block (Baseline vs. Reward)</td>
<td>Errors ($p &lt; .001$)</td>
<td>Errors ($p = .001$)</td>
</tr>
<tr>
<td>Reward AX-CPT</td>
<td>Trial-Based Effects on Task Performance: Errors</td>
<td>Incentive (Non-Incentive, Incentive) x Cue (A,B) x Probe (X,Y)</td>
<td>Incentive ($p &lt; .001$)</td>
<td>Incentive ($p &lt; .001$)</td>
</tr>
<tr>
<td>Reward AX-CPT</td>
<td>Trial-Based Effects on Task Performance: RTs</td>
<td>Incentive (Non-Incentive, Incentive) x Cue (A,B) x Probe (X,Y)</td>
<td>Incentive ($p &lt; .001$)</td>
<td>Incentive ($p &lt; .001$)</td>
</tr>
<tr>
<td>Reward AX-CPT</td>
<td>Trial-Based Effects on Task Performance: Proactive Indices (Errors and RTs)</td>
<td>Incentive (Non-Incentive, Incentive)</td>
<td>Incentive ($p &lt; .001$)</td>
<td>Incentive ($p &lt; .001$)</td>
</tr>
<tr>
<td>Emotion AX-CPT</td>
<td>Block-Based Effects on Task Performance: Errors</td>
<td>Block (Neutral, Positive) x Cue (A,B) x Probe (X,Y)</td>
<td>Block ($p = .572$)</td>
<td>Block ($p = .129$)</td>
</tr>
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</table>

Errors: $p < .001$, RTs: $p < .001$.
<table>
<thead>
<tr>
<th>Emotion AX-CPT</th>
<th>Block-Based Effects on Task Performance: RTs</th>
<th>Block (Neutral, Positive) x Cue (A,B) x Probe (X,Y)</th>
<th>Block (Neutral, Positive)</th>
<th>Cue x Probe ($p &lt; .001$) Block x Cue x Probe ($p = .198$)</th>
<th>Cue x Probe ($p &lt; .001$) Block x Cue x Probe ($p = .696$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emotion AX-CPT</td>
<td>Block-Based Effects on Task Performance: Proactive Indices (Errors and RTs)</td>
<td>Block (Neutral, Positive)</td>
<td>Emotion (Neutral, Positive) x Cue (A,B) x Probe (X,Y)</td>
<td>Emotion ($p = .630$) Cue ($p &lt; .001$) Probe ($p &lt; .001$) Emotion x Cue ($p = .452$) Emotion x Probe ($p = .768$)</td>
<td>Emotion ($p = .967$) Cue ($p &lt; .001$) Probe ($p &lt; .001$) Emotion x Cue ($p = .337$) Emotion x Probe ($p = .891$)</td>
</tr>
<tr>
<td>Emotion AX-CPT</td>
<td>Trial-Based Effects on Task Performance: Errors</td>
<td>Emotion (Neutral, Positive) x Cue (A,B) x Probe (X,Y)</td>
<td>Emotion ($p = .046$) Cue ($p &lt; .001$) Probe ($p &lt; .001$) Emotion x Cue ($p = .873$) Emotion x Probe ($p = .550$)</td>
<td>Cue x Probe ($p &lt; .001$) Emotion x Cue x Probe ($p = .283$) Errors ($p = .988$) RTs ($p = .216$)</td>
<td>Cue x Probe ($p &lt; .001$) Emotion x Cue x Probe ($p = .430$) Emotion ($p = .055$) Cue ($p &lt; .001$) Probe ($p &lt; .001$) Emotion x Cue ($p = .025$) Emotion x Probe ($p = .177$)</td>
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<tr>
<td>Emotion AX-CPT</td>
<td>Trial-Based Effects on Task Performance: RTs</td>
<td>Emotion (Neutral, Positive) x Cue (A,B) x Probe (X,Y)</td>
<td>Emotion ($p = .022$) Errors ($p = .115$) RTs ($p = .817$)</td>
<td>Errors ($p = .252$) RTs ($p = .013$)</td>
<td></td>
</tr>
<tr>
<td>Emotion vs. Reward AX-CPT</td>
<td>Block-Based Effects on Task Performance: Proactive Indices (Errors and RTs)</td>
<td>Session (Emotion, Reward) x Block (Neutral/Baseline, Positive/Reward)</td>
<td>Session ($p = .002$) Session x Block ($p &lt; .001$)</td>
<td>Session ($p = .141$) Block ($p &lt; .001$)</td>
<td>Session x Block ($p = .038$)</td>
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<td>Emotion vs. Reward AX-CPT</td>
<td>Block-Based Effects on Task Performance: Proactive Indices (RTs)</td>
<td>Session (Emotion, Reward) x Block (Neutral/Baseline, Positive/Reward)</td>
<td>Session ($p = .065$) Block ($p = .114$) Session x Block ($p = .013$)</td>
<td>Session ($p = .036$) Block ($p = .055$) Session x Block ($p = .002$)</td>
<td></td>
</tr>
<tr>
<td>Emotion vs. Reward AX-CPT</td>
<td>Trial-Based Effects on Task Performance: Proactive Indices (Errors)</td>
<td>Session (Emotion, Reward) x Trial (Neutral/Non-Incentive, Positive/Incentive)</td>
<td>Session ($p &lt; .001$) Trial ($p = .015$) Session x Trial ($p = .027$)</td>
<td>Session ($p &lt; .001$) Trial ($p = .008$) Session x Trial ($p &lt; .001$)</td>
<td></td>
</tr>
<tr>
<td>Emotion vs. Reward AX-CPT</td>
<td>Trial-Based Effects on Task Performance:</td>
<td>Session (Emotion, Reward) x Trial (Neutral/Non-Incentive, Positive/Incentive)</td>
<td>Session ($p &lt; .001$) Trial ($p = .191$) Session x Trial ($p = .546$)</td>
<td>Session ($p &lt; .001$) Trial ($p = .008$) Session x Trial ($p &lt; .001$)</td>
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</tr>
</tbody>
</table>
### PUPILLOMETRY ANALYSES

<table>
<thead>
<tr>
<th>Reward AX-CPT</th>
<th>Block-Based Effects on Pretrial Pupil (-200-0ms)</th>
<th>Block (Baseline, Reward)</th>
<th>Block (p = .053)</th>
<th>Block (p &lt; .001)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reward AX-CPT</td>
<td>Trial-Based Effects on Pupil at Cue Maintenance (2550-2800ms)</td>
<td>Incentive (Non-Incentive, Incentive) x Cue (A,B)</td>
<td>Incentive (p &lt; .001)</td>
<td>Incentive (p &lt; .001)</td>
</tr>
<tr>
<td>Emotion AX-CPT</td>
<td>Block-Based Effects on Pretrial Pupil (-200-0ms)</td>
<td>Block (Neutral, Positive)</td>
<td>Emotion (p = .563)</td>
<td>Emotion (p = .838)</td>
</tr>
<tr>
<td>Emotion vs. Reward AX-CPT</td>
<td>Block-Based Effects on Pretrial Pupil (-200-0ms)</td>
<td>Session (Emotion, Reward) x Block (Neutral/Baseline, Positive/Reward)</td>
<td>Session (p = .441)</td>
<td>Session (p = .008)</td>
</tr>
<tr>
<td>Emotion vs. Reward AX-CPT</td>
<td>Trial-Based Effects on Pupil at Cue Maintenance (2550-2800ms)</td>
<td>Session (Emotion, Reward) x Trial (Neutral/Non-Incentive, Positive/Incentive) x Cue (A,B)</td>
<td>Session (p &lt; .001)</td>
<td>Session (p = .008)</td>
</tr>
</tbody>
</table>

Incentive, Positive/Incentive = .199)
Incentive (p = .017)
Incentive x Cue (p = .117)
Incentive x Cue (p = .007)

Incentive x Cue (p = .007)
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