2-1-2016

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DISSOCIATION OF COGNITIVE CONTROL INSTANTIATION DUE TO

TEMPORAL DELAY

by

Jacqueline R. Janowich

B.A., Behavioral Neuroscience, Colgate University, 2009

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Science

Psychology

The University of New Mexico
Albuquerque, New Mexico

December, 2015

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ABSTRACT

Cognitive control is critical in adaptively guiding cognition, shaping an optimal balance between acting efficiently with existing rules, and remaining flexible enough to respond to new information. Proactive cognitive control utilizes context information to bias processing (in a top-down manner) and prepare for an upcoming event, presumably through dynamic use of highly related executive processes, including working memory maintenance, attention, and goal switching. Counter to the frequent investigation of proactive control as a unitary construct, we hypothesize that proactive control varies with the temporal delay over which goals need to be held in mind, and can be at least partly dissociated into separable neural processes. In the present experiment, we contrasted processing of cue context rules during short and long anticipated cue-probe delays. We hypothesize that rapid cue-probe delays would rely more on task-switching (rapid goal updating) processes, whereas longer cue-probe delays would rely more on active working

memory maintenance of cued goal information. EEG was used to dissociate the neural processes of post-cue task-switching and working memory maintenance utilized for each delay type. Integrating neural and behavioral data, we aim to provide a more nuanced account of proactive control, clarifying the distinct proactive control processes instantiated for different temporal delays.

Methods: Healthy undergraduate students (n=35) completed a variant of the AX-Continuous Performance Task (AX-CPT), assessing context processing in cognitive control, with short and long cue-probe delays. EEG data was recorded and ERP and time-frequency methods were used to analyze processing of cue information over short and long delays. **Results:** Accuracy was selectively impaired for rare probes following common cues ("AY") during short delay blocks. RT did not vary across cue/probe pairs, but as expected, showed a positive correlation with delay length. Cue-locked N1, N2, P2, and P3 ERP components revealed interactions between cue type and delay length. P1, N1, N2, and P2 components revealed interactions between delay length and task-switch vs. task-repeat trials. Mid-frontal theta phase consistency was positively correlated with proactive/reactive ratio for Short delay, suggesting elevated task-switching proactive control (TSPC). Conversely, delta power over the time-course of the P3 was dynamically elevated for cues preceding a long delay; delta power correlated with proactive/reactive ratio for only this Long delay condition, indicating use of WM-maintenance proactive control (WMMPC), and thereby revealing a double-dissociation between type of control and delay length. **Conclusions:** The present study demonstrates a double-dissociation in proactive control processes invoked by known short and long delays, with distinct cue-locked ERP and oscillatory components revealing context

updating and maintenance differences between delay conditions. These findings prompt

consideration that AX-CPT delay length biases different use of task switching, working

memory, and thereby proactive control type, and should no longer be conceived as a

unitary task across timing parameters.

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GENERAL INTRODUCTION

Cognitive control is a critical process in adaptively guiding cognition, continuously shaping an optimal balance between acting on existing rules, thereby promoting cognitive efficiency, and remaining flexible enough to respond appropriately to new information. Proactive cognitive control utilizes context information to bias processing (in a top-down manner) and prepare for an upcoming event, presumably through dynamic use of highly related executive processes, including working memory maintenance and goal switching. Counter to the frequent investigation of proactive cognitive control as a unitary construct, we hypothesize that proactive control varies systematically with the temporal delay over which goals need to be held in mind, and can be at least partly dissociated into separable neural processes.

In a world with a near-constant deluge of sensory inputs and ever-changing goals, use of context information to guide behavior is essential. However, as cognitive control uses substantial neural resources (for review, see (Shenhav, Botvinick, & Cohen, 2013), it is not efficient to apply proactive control in the same manner for temporally immediate events as to events more temporally distant. For instance, when given a temporally immediate rule, ie: "I am about to pitch you a [*curve* vs. straight] ball at 100 mph: swing if it is in the strike zone", it would be optimal to rapidly switch into "curve ball" mode (TSPC), so that you have sufficient time to prepare and react. In contrast, when given a promise from the pitcher that your next pitch, *after a 10-minute 7th inning stretch*, will be a curve ball, it would be best to instantiate a form of proactive control more reliant on working memory maintenance (WMMPC), in which the curve ball rule is held in working memory until it becomes behaviorally relevant.

Despite the intuitive understanding that different proactive control processes should be invoked based on the length of temporal delay before control must be applied, differences in invocation of proactive control based on anticipated delay length have not been systematically investigated. Further, although several recent studies have explored how greater rarity of a rule to be enacted (ie: a common straight ball vs. a rare curve ball) is associated with up-regulation of control processes, it is unknown how rule rarity interacts with expected delay, to modulate the type and timing of proactive control.

To address these questions of how anticipated timing modulates proactive cognitive control, we manipulate duration of cue-probe delay in a cognitive control task with rare and common cued context rules. EEG allows us to resolve with excellent temporal precision the constituent processes of proactive control, namely task switching and working memory, as they are invoked. Integrating neural and behavioral activity during each delay length, we can begin to dissociate different types of proactive control, dominated by either task-switching (TSPC) or working memory maintenance (WMMPC).

Dual Mechanisms of Control Framework, AX-CPT Paradigm, and Context Processing

The recent dual mechanisms of control (DMC) framework divides control into two distinct modes: proactive and reactive control, each important in enacting certain goal-directed behaviors. Proactive control involves sustained maintenance of goal-relevant information and enables the advance preparation of an optimal response. Reactive control, in contrast, favors a transient, stimulus-evoked re-activation of task goals, and results in slower, more variable responses (T. S. Braver, Paxton, Locke, &

Barch, 2009; T. S. Braver, 2012). These two processes are largely reciprocal; when proactive control to the contextual cue is lower, reactive control to the probe is greater, and vice versa. As preparatory control instantiation during the cue-probe delay is the focus of the present investigation, and reactive control, in contrast, is only observed after appearance of the probe stimulus, analyses and discussion in this work will be directed toward distinctions in proactive control. Re-integration of a non-unitary proactive control, as presented in this manuscript, into the DMC framework (ie: in relation with reactive control) will be addressed in the discussion.

To better understand how proactive control works, we can attempt to unravel distinctions in its underlying executive processes, task-switching and working memory, in situations demanding different types of preparatory control. The AX-Continuous Performance Task (AX-CPT) (Carter et al., 1998; J D Cohen, Barch, Carter, & Servan-Schreiber, 1999; J.D. Cohen et al., 1997) is a standard cue-probe cognitive task in which variance in cue and probe expectancy are used to assess the impact of (cue-derived) context on proactive and reactive cognitive control. AX-CPT is typically composed of 70% 'A-X' cue-probe 'target' pairs, and 10% each of 'A-Y', 'B-X', and 'B-Y' cue-probe 'non-target' pairs, generating a strong expectancy to respond according to the 'A-X' rule (Servan-Schreiber et al., 1996). 'A' and 'B' cues each introduce a different context, with distinct rules to follow for the common 'X' and 'Y' probe stimuli. AX-CPT is useful in investigating several related components of context-processing, including *context activation/updating, context maintenance, and context sensitivity*. Whereas context *activation/updating* involves dynamically instantiating and switching between contexts, *context maintenance* involves the active preservation of some context information over

time. *Context sensitivity* reflects how intensely context information biases a common probe stimulus. Manipulation of the delay between cue and probe (Cue-Probe Delay: CPD) has previously been used to assess context maintenance in cognitive control (for summary, please see (Barch et al., 2009)). In addition to the effect of CPD on context maintenance, this study addresses how CPD may also alter context activation and context sensitivity.

Cue-Probe Delay in AX-CPT

Cue-probe delays used in AX-CPT studies have varied widely (Figure S1), from 0 ms (Brambilla et al., 2007) to 9,500 ms (T Braver & Cohen, 2001), on average 3,162 +/- 2,444 (SD) ms, with this parameter given scarce discussion in most AX manuscripts. Germane to any use of AX-CPT to assess context processing, variation in CPD length across studies correlates with a significant difference in behavioral measures of context activation/updating (n=46 studies, r^2=.189). Importantly, this variance in task parameters is not equally distributed across studies: AX-CPT delay lengths differ between imaging modalities, such that fMRI AX studies use significantly longer cue-probe delays (n=15, mean= 4.56 s) than do non-fMRI (EEG and behavioral) studies (n=31, mean = 1.40 s) (p=0.0012**). Although delay length differences are incidental to the need for a longer delay time in fMRI and practical benefits to shortened trial length, these systematic differences in delay length render comparison across AX-CPT studies problematic.

Several recent AX-CPT studies have compared CPD lengths within-subjects (Barch et al., 1997; Beste, Domschke, Radenz, Falkenstein, & Konrad, 2011; T Braver &

Cohen, 2001; Ts Braver, Barch, & Cohen, 1999; Chung, Mathews, & Barch, 2011; Javitt, Shelley, Silipo, & Lieberman, 2000; Leary, Turner, & Andreasen, 2003; Lorsbach & Reimer, 2010; Lucenet & Blaye, 2014; Morales, Yudes, Gómez-Ariza, & Bajo, 2014; Paxton, Barch, Racine, & Braver, 2008; Paxton, Barch, Storandt, & Braver, 2006; Redick & Engle, 2011; Richard, Carter, Cohen, & Cho, 2013). Of note, most studies varied CPD in a block-wise manner, whereas a few studies interspersed long and short delays within experimental blocks (D'Ardenne & Eshel, 2012; Javitt et al., 2000; Redick & Engle, 2011). In addition, in much of the work comparing CPDs, total trial length was balanced between CPD conditions by adjusting the Inter-Trial Interval (ITI) (ie: short CPDs were paired with long ITIs) (Barch et al., 1997; T. S. Braver, Satpute, Rush, Racine, & Barch, 2005; Paxton et al., 2008; Redick & Engle, 2011). Manipulating both CPD and ITI, while equating total trial time and block length, can not specifically address the impact of CPD on proactive cognitive control, as it is difficult to disentangle the impact of CPD and ITI on task-updating processes involved in switch trials. In the present study, to specifically interrogate the effects of *anticipated* CPD length on preparatory proactive control, CPD was kept the same within each set of delay blocks, and ITI was held constant across CPD lengths.

Neural Mechanisms of Cognitive Control

Neuroimaging offers a valuable mechanistic perspective on how cognitive control is initiated, especially during the CPD, during which no behavior is observed. A growing body of literature has investigated the behavioral correlates and neural mechanisms of

cue-based task instantiation and switching (for reviews, see (Karayanidis et al., 2010; Kiesel et al., 2010)).

The fMRI literature has localized with excellent spatial precision the brain regions involved in instantiating and enacting control. In general, anterior cingulate cortex's (ACC) alarm, signaling detection of conflict and the need for control (Kerns et al., 2004), activates DLPFC to resolve interference (Botvinick, Braver, Barch, Carter, & Cohen, 2001), and DLPFC biases posterior-parietal areas to enact context-appropriate behavior. After an informative cue, activation of ACC during the CPD (which may be sustained throughout even a long CPD), is correlated with faster task performance (Sohn, Albert, Jung, Carter, & Anderson, 2007), suggesting that this early CPD ACC activity facilitates conflict processing.

In other AX-CPT fMRI studies, the timing of lateral PFC (lPFC) activity has differentiated the use of proactive vs. reactive control, with proactive control characterized by sustained and/or anticipatory lPFC activity during the CPD (T. S. Braver et al., 2009; Paxton et al., 2008). Importantly, differences in the temporal delay over which control needs to be maintained have been reflected in differential CPD activation within the lPFC. Per the *information cascade hypothesis*, the anterior lateral PFC (DLPFC) is activated to task cues temporally remote from action selection, whereas posterior lateral PFC (VLPFC) is activated for cues in close temporal proximity to action selection (Reynolds, O'Reilly, Cohen, & Braver, 2012). Alternatively, the *adaptive context maintenance hypothesis* posits that both anterior (BA 9/44/46; DLPFC) and posterior (BA 6; VLPFC) lPFC activation is flexible according to task demands, with temporal dynamics of activation (of both regions) modulated by current demands for

maintenance duration (Reynolds et al., 2012). The differential activation of VLPFC and DLPFC to short and long CPDs may be related to their differential involvement in task-switching vs. working memory. VLPFC is strongly implicated in cue-based task-switching (Brass & von Cramon, 2002; M F S Rushworth, Hadland, Paus, & Sipila, 2002). Anterior to VLPFC, DLPFC (BA 46/9) has been found as a locus for the maintenance component of WM (Cohen et al., 1997; Courtney et al., 1997; Fiez et al., 1996), in some cases specifically for control-demanding trials (a W. MacDonald, Cohen, Stenger, & Carter, 2000). In fMRI studies varying CPD between blocks, longer CPD (8000 ms) was found to evoke more activation in left DLPFC (BA 46/9) relative to short CPD (1000 ms) (Barch et al., 1997; T Braver & Cohen, 2001), suggesting delay-mediated differences of WMM processes.

Although a substantial body of fMRI literature has detailed the involvement of ACC, VLPFC, and DLPFC in various aspects of cognitive control during CPD, the lack of temporal specificity in fMRI leaves many questions unanswered regarding the timing of this activity, especially during short CPDs in which extraneous (non-CPD) activity is necessarily captured during the longer MR sequence. The current EEG study offers the excellent temporal resolution to better resolve how (in particular, when) anticipated CPD information is used to bias context processing.

Cue-Locked EEG:

Several event-related potential (ERP) components have been implicated in cue processing, hypothesized to consist of sensory, evaluative, and preparatory components (Meiran, Chorev, & Sapir, 2000). To understand how and when anticipated CPD

modulates instantiation of proactive control, we evaluate ERP and oscillatory components at each stage of cue processing. We seek to resolve which early sensory, evaluative, and/or later preparatory cue-processing modulations underlie differences in TSPC and WMMPC?

Sensory

 Early cue "sensory" processing has been reported from 0-200 ms post-cue onset, to include visual ERP components P1 and N1 (Di Russo et al., 2002, 2003), and has been computed at parietal-occipital PO3 and PO4 (Bickel, Dias, Epstein, & Javitt, 2012). A slightly later, anterior component, referred to as the Early Anterior Positivity (EAP), with similarities to the Frontal Selection Positivity (FSP) and P2a (Potts et al., 2004; Potts & Tucker 2001) is maximal at Fz around 150-200 ms post-cue (Duncan E Astle, Jackson, & Swainson, 2008; Lavric, Mizon, & Monsell, 2008), and seems to be an early evaluator of stimulus relevance.

Evaluative

A cue-evaluation window from 200-500 ms post-cue includes alpha event-related desynchronization (ERD) in parietal-occipital areas (Bickel et al., 2012), associated with attention and memory (Klimesch et al., 2003; Schack et al., 2005) and a gradual release of inhibition (Klimesch, Sauseng, & Hanslmayr, 2007). In other work, ERD was seen in the superior frontal gyrus (BA 6), corresponding to an increase in alpha power (Crespo-Garcia et al., 2013). ERD onset is negatively associated with P3 amplitude and positively associated with P3 latency (Yordanova et al., 2001).

Overlapping the cue-evaluation window, P3b, observed at central-parietal sites (Pz) from 240-640 ms post-cue (Beste et al., 2011; Dias, Foxe, & Javitt, 2003; Javitt et

al., 2000; Schmitt, Wolff, Ferdinand, & Kray, 2014; Tekok-Kilic, Shucard, & Shucard, 2001; van Wouwe, Band, & Ridderinkhof, 2011), is associated with context maintenance and WM updating (Hartikainen and Knight 2003, Kok 2001, Polich 2003, Polich 2007; Knight 1996). For rare cues, P3b peaks later and has greater amplitude (Morales et al., 2014; van Wouwe et al., 2011), especially during a short CPD (Morales et al., 2014). P3 is composed of phase-locked delta and theta (Basar-Eroglu 1992; Kolev 1997; da Silva 1999; Pfurtscheller 1996; Yordanova & Kolev 1998), and of which delta is the strongest contributor (Demiralp, Ademoglu, Schürmann, Başar-Eroglu, & Başar, 1999).

The differential switch positivity (D-pos), and the late parietal positivity (LPP) (Duncan E Astle et al., 2008; M F S Rushworth et al., 2002; Matthew F S Rushworth & Behrens, 2008) are similar components observed during the CPD in cases of a change in *intended* performance (D. E. Astle, Jackson, & Swainson, 2006). D-pos peaks between 200-600 ms at central-parietal sites (Karayanidis, Coltheart, Michie, & Murphy, 2003), and larger amplitude is related to shorter decision and non-decision times on switch-to trials (Karayanidis et al., 2009). D-pos amplitude varies between CPDs (Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005); this has been explained by the reduced time pressure in long CPD condition, which enables preparatory activity to vary more widely across participants (and trials), and results in the smaller amplitude, broader D-pos component (Nicholson et al., 2005). For task-switch trials, a sustained central and posterior positivity has also been reported, between 520-1080 ms after cue presentation (M F S Rushworth et al., 2002; M. F. S. Rushworth, Passingham, & Nobre, 2005). Comparing neural activity during cue evaluation is important in resolving how cue content (common or rare task) and context (preceding a known short or long delay)

informs subsequent preparation for task-switching and working memory maintenance processes.

<u>Preparation</u>

The contingent negative variation (CNV) component derives in part from the pre-SMA and surrounding VLPFC areas (Gomez 2003, Rektor 2004), is correlated with beta power (Bickel et al., 2012), and is primarily observed at fronto-central sites ((Beste et al., 2011; Bickel et al., 2012; Dias et al., 2003; Hämmerer, Li, Müller, & Lindenberger, 2010) during the CPD (Dias et al., 2003). CNV is hypothesized to reflect preparatory activity, and is correlated with RT (Bickel et al., 2012). Intriguingly, CNV amplitude varies with CPD, with higher amplitudes during shorter delays (1200 vs. 2400 ms) (McAdam, Knott, & Rebert, 1969).

In addition to the aforementioned activity at particular sensory, evaluative, and preparatory phases of cue processing, certain oscillatory activity is sustained throughout delay duration. Sustained theta activation has been observed for WM maintenance throughout a delay period (Raghavachari et al., 2001), though this effect may be selective for sequential WM tasks. Gamma oscillations appear to more generally correspond to WM maintenance ((Pesaran, Pezaris, Sahani, Mitra, & Andersen, 2002); for review: (Roux & Uhlhaas, 2014)).

Each EEG signature of cue processing, including task-switching and working memory components, builds toward an understanding of how cues are dynamically used to inform context adaptation and maintenance across the CPD. By comparing EEG activity during known short and long CPDs and for cues requiring different types of

proactive control, we can use EEG signatures indicative of TS and WM to dissociate how cognitive control instantiation processes differ based on the delay over which context is to be maintained.

Goals and Hypotheses

The present study investigates behavioral and neural differences in control instantiation ahead of known short and long temporal delays. We hypothesize that the type of proactive control used (TSPC vs. WMMPC) will vary between short and long delay lengths, and that EEG activity at cue sensory, evaluation, and preparation phases will dissociate the early task switching and working memory mechanisms of instantiating these distinct control networks. In particular, we predict that EEG during short CPD will be characterized by a rapid task-updating (TSPC) type of proactive control, and long CPD by a prolonged working memory maintenance (WMMPC) type of proactive control.

METHODS

Participants:

Thirty-five undergraduate students at the University of New Mexico (26 women, ages 18-42 years, mean 19.8 +/- SD 3.4 years) participated in this experiment. Demographic information is displayed in Table 1. Participants reported no current use of psychiatric or neurological medication, no history of head injury or epilepsy, and normal or corrected-to-normal vision. All participants were right handed (Hand Usage Questionnaire mean=37.9, min=34 (max possible score = 39)). Data from two participants were excluded from EEG analyses: one due to technical problems with the EEG equipment, and one due to excessive noise in the EEG data. The University of New Mexico Institutional Review Board approved this experiment. Participants provided written informed consent and received course credit for their participation.

Table 1. Mean (SD) of sample demographic information. N=35.

Age (years)	19.83 (3.40)
Education (years)	13.40 (1.27)
Gender	26 F, 9 M
Handedness	35 R
Delay First	Short = 18; Long = 17

Cognitive/Behavioral Task:

The AX-Continuous Performance Task (AX-CPT) (Carter et al., 1998; J D Cohen et al., 1999; J.D. Cohen et al., 1997) is a standard cue-probe cognitive task in which variance in cue and probe expectancy are used to assess the impact of (cue-derived) context on cognitive control.   The task flow and parameters are depicted in Figure S2. In this task, a probe stimulus ('X' or 'Y') was presented following a paired cue stimulus ('A' or 'B') in 'target' and 'non-target' combinations. In a two-alternative-forced choice manner (2AFC), participants were instructed to respond to both cue and probe stimuli with left or right trigger buttons on a joystick. In the target 'AX' sequence, 'X' probes following 'A' cues demanded a 'right' trigger press; all other cues and probes were to be responded to with the 'left' trigger. Because 70% of trials were composed of 'A-X' cue-probe 'target' pairs, entailing a 'left-right' cue-probe response sequence, and 'A-Y', 'B-X', and 'B-Y' cue-probe 'non-target' pairs were much more rare (10% trials of each), a strong expectancy was generated to respond according to the 'A-X' rule (Servan-Schreiber et al., 1996). Error feedback ("ERROR!") followed any Cue error or non-response. Feedback in the form of a green (correct) or red (incorrect or too late) crosshairs immediately followed each probe response (or time-out after non-response), for 500 ms. Trials were separated by a jittered inter-trial interval of 750-1000 ms.

A key feature of this variant of the AX-CPT paradigm is the block-wise comparison of short and long delays between cue ('A' or 'B') and probe ('X' or 'Y') stimuli. In the short delay condition, a static 750 ms delay separated the cue and probe stimulus. In the long delay condition, the probe was presented ~3000 ms after the cue (randomly jittered between 2500-3500 ms, interval of 50 ms). All participants completed

both short and long delay conditions, with delay order randomly assigned and counterbalanced between participants.

After being instructed in AX-CPT task rules by the experimenter, participants completed a practice session of 25 (short delay) trials. Participants were then given delay-specific instructions for the first delay condition ('Delay 1'), and completed five blocks of 50 trials (total 250 trials) of 'Delay 1' with short breaks offered between each block. Instructions for the second delay condition ('Delay 2') were then presented, followed by five blocks of 50 trials (total 250 trials) of 'Delay 2', with short breaks offered between each block. Total task duration was 41.7 minutes (+/- 3.4 mins). Our task was written in Matlab, using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007).

Cue-Based Analyses:

Two sets of cue-based comparisons were performed on this data: 1) A vs. B cues, to distinguish instantiation of common vs. rare rule sets between CPD lengths, and 2) processing of repeat (A-post-A) vs. switch trials (A-post-B), to identify how CPD differences mediate switch processing. Trials were divided into four conditions for each set of comparisons: "Short A (or A-postA)", "Short B (or A-postB)", "Long A (or A-postA)", and "Long B (or A-postB)". Two-way repeated measures ANOVAs were used to calculate statistical main effects of cue type and delay length, and cue-delay interactions. Correlations between neural and behavioral variables were computed with Pearson's R. To assess statistical differences in correlations between Short and Long delay lengths, within-sample rho-to-z tests (Lee & Preacher, 2013; Steiger, 1980) were

conducted; these tests incorporate a variable describing how the two tests are themselves

correlated, and are preferred for non-independent correlations.

Behavioral Analyses:

  Context activation/updating was quantified with the Behavioral Shift Index (BSI) (T. S. Braver et al., 2009) (used in (Chiew & Braver, 2013; Edwards, Barch, & Braver, 2010; Lamm et al., 2013; Lucenet & Blaye, 2014; Morales et al., 2014; Schmitt et al., 2015)), which indexes the proportional use of proactive versus reactive control based on task error rate or reaction time to "AY" relative to "BX" cue-probe pairs. The following formula generates a single proactive/reactive Behavioral Shift Index value:

  aY – bX / (aY + bX)

  Higher BSI scores are associated with a greater use of Proactive Control, whereas lower BSI scores are associated with a greater use of Reactive Control. Prior literature suggests that proactive control in AX-CPT should be characterized by activation of the cued context ("A" or "B"), and preparation during the CPD to respond according to the cued rule. If context activation/updating abilities are intact, proactive control should bias responses based on context (Ts Braver et al., 1999) and manifest in impaired performance on 'AY' trials (T. S. Braver et al., 2005), during which a robust pre-potent response must be inhibited.

  Signal Detection Metrics, quantified by sensitivity d-prime (d') scores, response bias 'B' scores, and criterion location 'C' scores, were used to contrast how response criteria differ between probe types aY and bX, presumably requiring different variants of cognitive control (inhibit pre-potent cued response to adapt to a rare probe, versus maintaining a rare cue to respond to a common probe, respectively). Critically, we investigated how this might vary based on the length of the cue-probe delay.   To evaluate whether signal detection criteria are modulated by CPD, we compared

sensitivity, response bias, and criterion location scores across delay conditions, and

sought to find if neural activity during the CPD could predict context sensitivity in either

delay condition.

EEG Data Acquisition:

EEG data were acquired with a BrainVision 64-channel amp, with standard 10-20

configuration, and recorded with PyCorder software. Data were recorded continuously

across 0.1-100 Hz and sampled at 500 Hz. VEOG was recorded above and below the

right eye. FPz was utilized as online ground, and CPz served as a secondary online

reference.

EEG Data Pre-Processing:

Epochs were created surrounding cue onset (-2000 : 7000 ms), from which

associated cue and probe responses, as well as cue-probe delay activity, were isolated.

After data were re-referenced to average reference, CPz was re-created. Several channels

(FT9, FT10, TP9, TP10) were removed, due to their unreliability and location above or

behind the ear, from which neural activity is difficult to infer. Additional bad channels

were identified using a combination of FASTER (Nolan, Whelan, & Reilly, 2010) and

eeglab's pop_rejchan (Delorme & Makeig, 2004), and interpolated. Data were again re-

referenced and average and bad epochs, as identified by FASTER, were then rejected.

ICA (runica) was run to identify bad components; VEOG activity and a Gaussian

template around frontopolar channels was compared with ICs to identify and reject blink

activity.

A wavelet transform was applied to the data, enabling precise temporal resolution of the frequency information, and directly revealing the oscillatory amplitude and phase (Herrmann, Grigutsch, & Busch, 1999).

ERP & Time-Frequency Analyses

Event-related potentials (ERPs) were created to assess with temporal precision the early post-cue activity involved in instantiating proactive control. Cue-locked activity for each condition (see above) was calculated as an average of all trials with correct responses to both cue and probe, ensuring attention to the task and successful context processing. Trial count was equalized between conditions, to account for the far greater number of A vs. B trials. Epochs were created from -2000:2000 ms peri-cue, and activity was baseline-corrected to -200:0 ms pre-cue. The ERP components chosen for analysis were selected based on prior literature suggesting their involvement in task-switching or working memory processes. ERP components were evaluated at a priori regions of interest, and group-mean maximal values *across conditions* were used to derive common windows of interest for further analysis. For P1, N1, P2, and N2 components, windows were taken for 20 ms around the across-condition peak. For the more temporal diverse P3 components, windows were established at 40 ms surrounding the across-condition peak. For each component of interest at each electrode of interest, individual peaks were identified from the across-condition time windows.

For all ERP and time-frequency analyses, we derived estimates of the Current Source Density (CSD) by computing the Surface Laplacian of the spherical-spline interpolated scalp topography *(laplacian_perrinX.m)* (Perrin, Pernier, Bertrand, &

Echallier, 1989). As a high-pass spatial filter, the Surface Laplacian filters out spatially

broad features, thereby minimizing effects of volume-conduction, and highlights local

topographical features. The Surface Laplacian is reference-free, and as such avoids

confounds with the choice of reference electrode (M. X. Cohen, 2014a; Kayser & Tenke,

2006, 2015). After Laplacian spatial transform, wavelet transforms were applied to cue-

locked EEG data, to identify time-frequency oscillatory activity in the delta (1-4 Hz),

theta (4-7 Hz), and alpha (8-13 Hz) frequency bands. As temporal smoothing from time-

frequency decomposition may introduce temporal leakage of trial-related activity into the

pretrial period (M. X. Cohen, 2014b), all time-frequency analyses were conducted with a

baseline time period of -300 : -100 ms peri-cue.

Results:

AX-CPT Behavior

Behavioral metrics of interest: accuracy, reaction time, and reaction time variability (standard deviation) were computed for the 2AFC responses to Cue and Probe, and averaged across experimental blocks for each Delay Length.

To evaluate the influence of Cue Type (A vs B), Delay Length (Short vs Long), and Cue x Delay Interaction on AX-CPT performance, two-way repeated measures ANOVAs were computed for each behavioral metric. Group means and SDs of AX-CPT behavioral metrics for each Cue Type and Delay Length, as well as significance levels derived from p-values from two-way repeated measures ANOVAs (Cue Type x Delay Length) are displayed in Table 2.

In addition, several AX-CPT summary measures were computed based on a combination of A-cued and B-cued probe behavior. For each of these measures, the effect of Delay Length was evaluated with a one-way repeated measures ANOVA. Mean values and standard deviations for each metric, and rm-ANOVA p significance values are enumerated on Table 3.

Table 2. AX-CPT Behavioral Measures with Mean (SD) and Two-way rm-ANOVA p significance levels

AX-CPT Metric	Short "A"	Long "A"	Short "B"	Long "B"	Main Effect Cue Type	Main Effect Delay	Cue-Delay Interaction
Cue Accuracy	.997 (.004)	.994 (.007)	.990 (.020)	.995 (.014)	n.s.	n.s.	*
Cue SD of Acc	.004	.007	.020	.014			
Cue RT (sec)	.248 (.043)	.424 (.097)	.290 (.067)	.478 (.112)	***	***	n.s.
Cue SD of RT (sec)	.091 (.023)	.191 (.100)	.118 (.022)	.183 (.095)	n.s.	***	***
Probe X Acc	.953 (.036)	.878 (.123)	.958 (.040)	.874 (.151)	***	n.s.	n.s.
Probe X RT (sec)	.310 (.035)	.468 (.103)	.287 (.100)	.472 (.175)	n.s.	***	n.s.
Probe X SD of RT (sec)	.091 (.025)	.186 (.102)	.115 (.038)	.241 (.152)	***	***	n.s.
Probe Y Acc	.736 (.164)	.875 (.114)	.975 (.055)	.974 (.044)	***	***	***
Probe Y RT (sec)	.381 (.050)	.557 (.098)	.277 (.083)	.453 (.143)	***	***	n.s.
Probe Y SD of RT (sec)	.114 (.037)	.163 (.075)	.098 (.024)	.189 (.145)	n.s.	***	n.s.

*= p-value <0.05; *** = p-value <0.0001.*

Table 3. Behavioral Summary Metrics: One-way rm-ANOVA Comparisons between Delay lengths

| Summary Metric	Short Delay	Long Delay	1-way rmANOVA
Behavioral Shift Index (acc)	0.417 (.528)	0.147 (.711)	n.s. #
Behavioral Shift Index (RT)	-0.067 (.063)	-0.059 (.173)	n.s.
d' (sensitivity) for aY	2.506 (.809)	3.503 (1.387)	p<.0001; F=31.96
B (response bias) for aY	-1.261 (.548)	-0.786 (2.415)	n.s.
C (criterion location) for aY	-0.534 (.232)	-0.273 (.489)	p=.005; F=9.36
d' (sensitivity) for bX	3.533 (1.366)	3.842 (1.789)	n.s.
B (response bias) for bX	0.582 (2.660)	0.146 (2.568)	n.s.
C (criterion location) for bX	-0.020 (.588)	-0.104 (.552)	n.s.

 # = p-value <0.07

Cue Behavior:

Cue error rates and reaction times are displayed in Figure 1. For accuracy in responding to Cue, no main effects of Cue Type (p=0.078; F=3.323) nor Delay Length (p=0.692; F=0.160), were observed, though there was a significant interaction between Cue and Delay (p=.0163; F=6.430). However, because both Cue Type accuracies were nearly at ceiling (mean A=0.996; mean B=0.992), their statistical differentiation is not discussed further.

Cue RT was significantly greater for Long (0.479 +/- 0.113 seconds) than Short (0.236 +/- 0.005) Delay (p<.0001; F=68.647). A main effect of Cue Type (A=0.336 +/- 0.116 seconds; B=0.384 +/- 0.132 seconds) (p<.0001; F=97.401) was also observed. No interaction was found between Cue and Delay on Cue RT (p=0.112; F=2.673).

For Cue RT-SD, a main effect of Delay Length was found (p=<.0001; F=31.941), with Long Delay (0.187 sec eliciting greater RT-SDs than Short Delay (0.105 sec.). No main effect of Cue Type was observed on Cue RT-SD (p=0.073; F=3.442). A Cue-Delay interaction was found for Cue RT-SD (p<.0001; F=13.21).

Figure 1. Cue Error Rates and Reaction Times by Cue Type and Delay Length
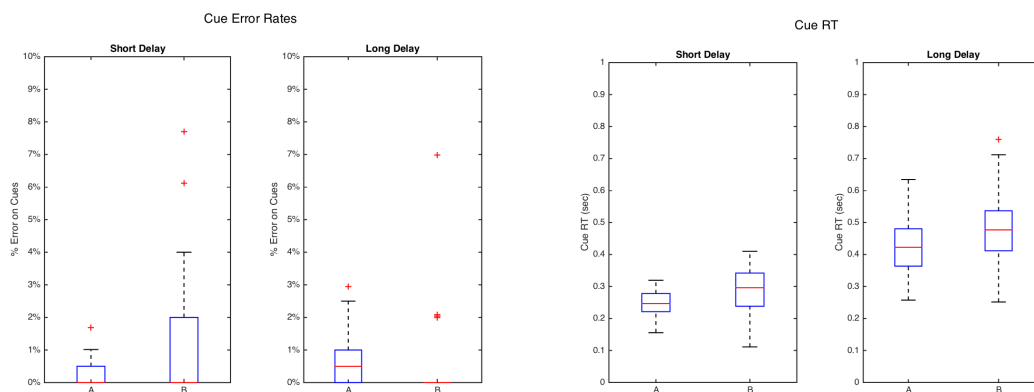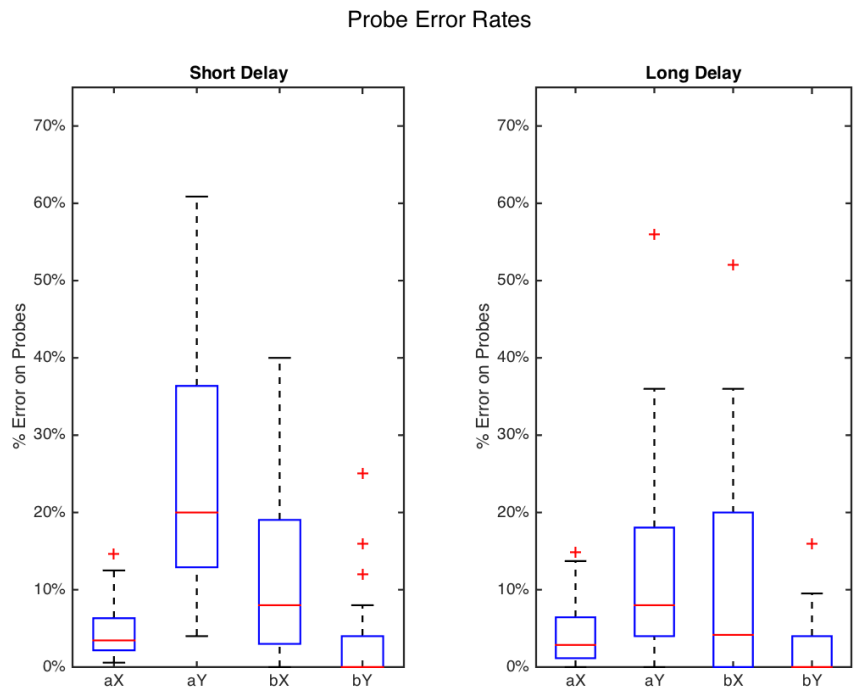
Probe Behavior:

Probe error rates and reaction times are depicted in Figure 2. Accuracy to X probe was significantly greater when X was preceded by the A cue (0.956 +/- 0.038) vs B cue (0.876 +/- 0.140), indicating a main effect of Cue Type (p<.0001; F=22.097). No main effect of Delay Length on X accuracy was observed (Short = 0.915 +/- 0.102; Long = 0.916 +/- 0.118) (p=.969; F=.002). No Interaction between Cue Type and Delay Length on X accuracy was observed (p=.749; F=.104).

Accuracy to Y probe was significantly decreased when Y was preceded by A cue (0.805 +/- 0.156) vs B cue (0.975 +/- 0.050), indicating a main effect of Cue Type (p<.0001; F=76.272). A main effect of Delay Length on Y accuracy was also observed (p<.0001; F=30.654), with decreased accuracy in Short (0.856 +/- 0.171) vs Long delay (0.924 +/- 0.099). A significant interaction between Cue Type and Delay Length was observed (p=<.0001; F=28.939), with participants demonstrating selective impairment for Y probes following A cues, during Short Delay (0.736 +/- 0.164).

Main effects of Delay Length were observed for both X (p<.0001; F=66.386) and Y (p<.0001; F=78.3355) probes, with Long Delay generating longer probe RTs (Long X= 0.470 +/- 0.143; Long Y= 0.505 +/- .132) than Short Delay (Short X = 0.298 +/- 0.075; Short Y= 0.329 +/- 0.086). A main effect of Cue Type on probe RT was found for Y (a-Y = 0.469 +/- 0.118; b-Y = 0.365 +/- 0.146) (p<.0001; F=75.7921), but not X probes (a-X= 0.389 +/- 0.110; b-X=0.379 +/- 0.169) (p=.503; F=.458). No significant Cue Type x Delay Length interactions were observed for X (p=.159; F=2.079) or Y (p=.972; F=.0013) RTs.

Figure 2. Probe Error Rates and Reaction Times by Probe Type and Delay Length

a.

Probe Error Rates

b.

Probe RT
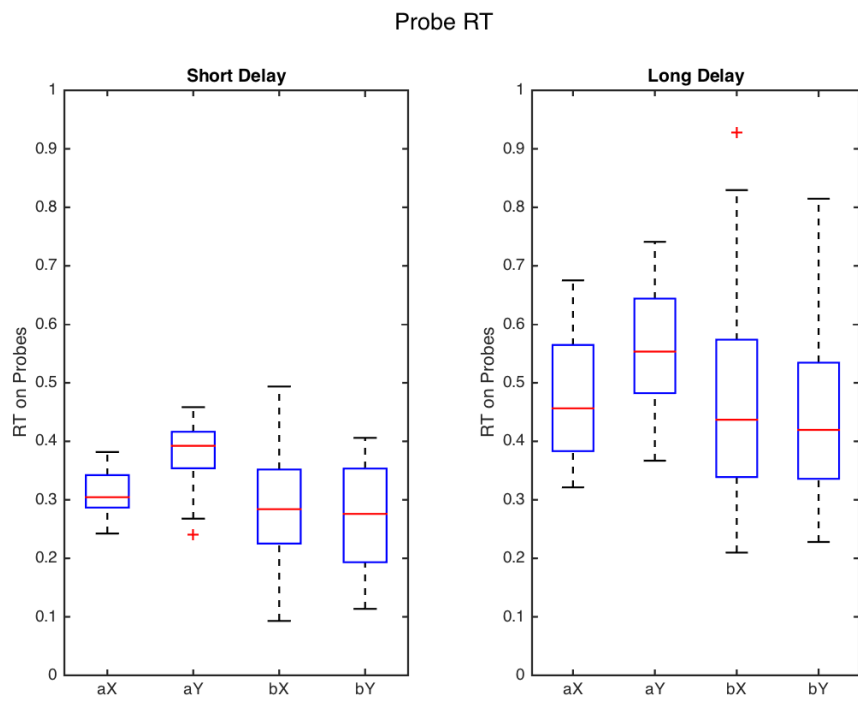
Summary Behavioral Measures

Behavioral Shift Index boxplots are displayed in Figure 3. With a one-way rm-ANOVA, no significant Delay Length differences were found for the Behavioral Shift Index (BSI) (T. S. Braver et al., 2009) (see Methods), although there was a trend for a higher error rate BSI (BSI-ER) (p=.089; F=3.085) in Short Delay, indicating a greater reliance on proactive control. Reaction time BSI (BSI-RT) did not differ between Short and Long delays (p=.779; F=.080).

Signal detection measures (d prime, Beta, C) were computed at each delay length for probes demanding high levels of cognitive control: 'a-Y' and 'b-X'. Signal detection boxplots are displayed in Figure 4. One-way repeated measures ANOVAs were calculated to compare each signal detection measure between delay lengths, and two-way repeated measures ANOVAs were used to determine if there was an interaction between probe type and delay length on each signal detection measure.

d prime (d'), indicating response sensitivity, was computed by subtracting z score for false alarm rate from z score of hit rate:

$$d' = \Phi^{-1}(H) - \Phi^{-1}(F).$$

(Stanislaw & Todorov, 1999). One-way rm-ANOVAs indicated a significant effect of delay length for on d' for 'aY' probes (p<0.0001; F=31.955), whereas no significant effects were found for 'bX' probes (p=0.393; F=0.7488). Two-way rm-ANOVA revealed a significant main effect of probe type (aY= 3.004 +/- 1.234; bX= 3.687 +/- 1.587; p<0.0001; F=13.546), no main effect of Delay Length (p=0.0054; F= 8.9153), and a marginally significant interaction between probe type and delay length (p=0.0612; F=3.7637).

Beta (B), a measure of response bias, was calculated as:

$$\beta = e^{\left\{\frac{\left[\left[\Phi^{-1}(F)\right]^2 - \left[\Phi^{-1}(H)\right]\right]^2}{2}\right\}},$$

(Stanislaw & Todorov, 1999). Low beta reveals a tendency to over-respond (impulsively), whereas high beta reveals a (cautious) under-responding. Beta did not differ between delay lengths for 'aY' (p=0.282; F=0.526) nor 'bX' probes (p=0.482; F=0.298). Two-way rm-ANOVA reveals a significant effect of probe type (p<0.0001; F=12.666) on Beta, while there is no effect of delay length (p=0.953; F=0.036), and no probe type x delay length interaction (p=0.288; F=1.168).

C is an indicator of decision criterion, and is calculated as the signed difference between the actual decision threshold and that of the ideal observer:

$$c = -\frac{\Phi^{-1}(H) + \Phi^{-1}(F)}{2}.$$

A C of zero models an "ideal observer", while a more negative C demonstrates a liberal over-responding, and a more positive C points to a conservative under-responding (Abdi, 1966; Stanislaw & Todorov, 1999). In the present data, 'aY' probe C is significantly more negative in Short vs. Long Delay (p=0.005; F=9.360), indicating liberal over-responding specifically in Short Delay. 'bX' probe, in contrast, demonstrates no difference in decision criterion between delay lengths (p=0.541; F=0.381). Two-way rm-ANOVA shows a marginally significant interaction between probe type and delay length for C (p=0.061; F=3.764).

Figure 3. Behavioral Shift Index derived from Error Rate (Panel A) and RT (Panel B) for Short and Long delays
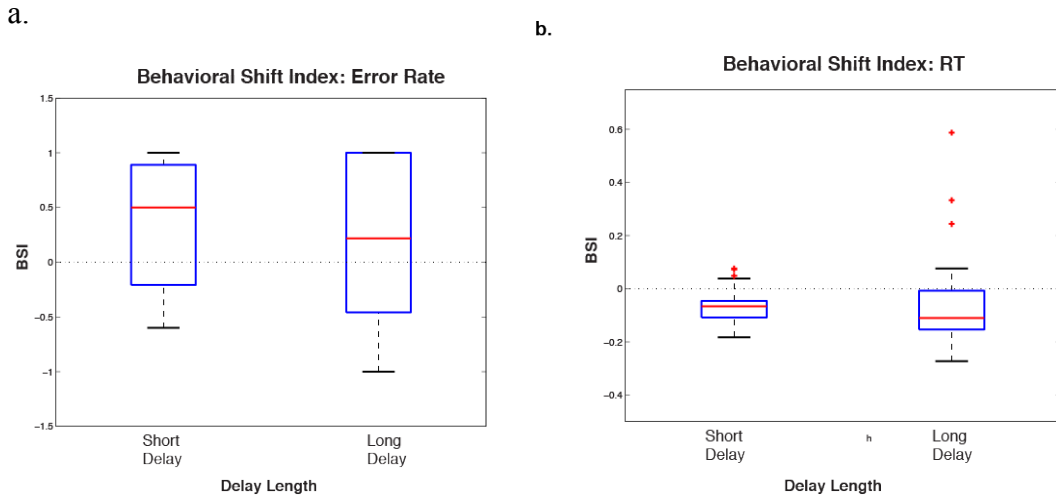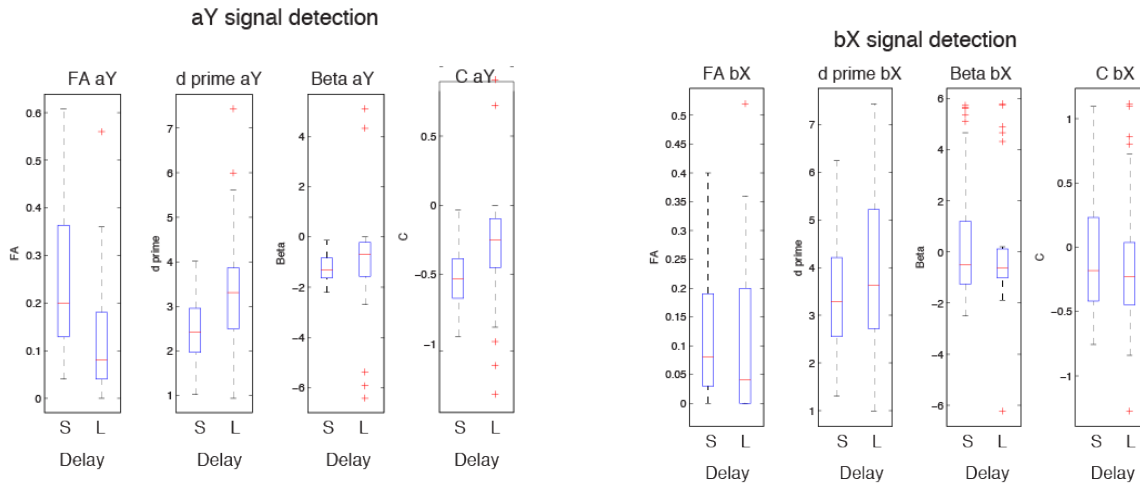
a.

b.

Figure 4. Signal Detection: False Alarm rate (FA), d' (response sensitivity), Beta (response bias), and C (decision criterion) by Delay Length for aY and bX probes

EEG Results

To compare neural activity during the cue-probe delay Cue Type and Delay Length, ERP peak amplitudes were contrasted using two-way rm-ANOVAs. In addition, by contrasting A cues following B cues (task-switch: A-PostB) versus A cues following A cues (task-stay: A-PostA), we sought to determine whether task-switching properties were activated differently for short versus long delays.

P100, an early marker of attention and perceptual processing, showed a selective increase in amplitude for Short cues at posterior-parietal electrodes PO3, PO7, and PO8, which was maximal at PO7 (Figure 5) (Delay Length main effect at PO7: $p < .001$; $F = 15.748$). A significant main effect of Cue Type, with greater amplitude for rare B cues, was also observed at PO7 and PO8, maximally at PO7 ($p = 0.001$; $F = 12.711$). A marginal Cue Type x Delay Length interaction was found at PO8 ($p = .076\#$; $F = 3.372$). Evidence for behavioral relevance of the early attention P1 components was found for Long delay: P1 amplitude at PO7 significantly predicted d' (sensitivity) for Long A cues ($r^2 = .596$) and Long B cues ($r^2 = .345$), but not Short A ($r^2 = .157$) or Short B cues ($r^2 = .144$). No main effect of task-switching or interaction of task-switching with delay length was observed.

N100, an early indicator of attention, was observed maximally at central posterior POz. A marginally significant interaction between Cue Type and Delay Length revealed a greater (more negative) N100 deflection for Short, Rare Cues ($p = .091\#$; $F = 4.382$). In addition, there was a significant interaction between task-switching (A-PostA vs. A-PostB) trial type and Delay Length ($p = .026$; $F = 5.749$), which closely matched the A vs. B cue findings: task-switching A-PostB cues in Short delay were processed with the

greatest (most negative) N100 deflection. The similarity between the Short B cue and Short A-PostB cue processing may suggest a similar task-switching signal for B and A-PostB cues, specific to the Short Delay condition.

Peak amplitudes of mid-frontal P200, involved in control instantiation and task-switching, were assessed (Figure 7). P2 peak amplitude at FCz is greater for cues at Short vs. Long Delay (p=.002; F=10.972). The significant main effect of Delay Length is repeated for task-switching P2 amplitude (p<.0001; F=21.001). There was a marginal effect of task-switching (A-PostB > A-PostB) on P2 amplitude (p=0.053; F=4.045), and no interaction between task switching and Delay Length (p=.189; F=1.798).

N2 troughs, a marker of cognitive control, were found to be maximal (most negative) at anterior central AFz (Figure 8). Marginally significant main effects of Cue Type (p=0.084; F=3.181) and significant effects of Delay Length (p=.004; F=9.664) are found, such that B cues and Short Cues generate negative N2s. A Cue Type x Delay Length interaction is also observed, with Short B cues evoking the most extreme N2s (p=0.019; F=6.105). For task-switch A-PostB versus task-stay A-postA, N2 was marginally amplified (more negative) for task-switch A-PostB trials than A-PostA trials (p=.060; F=3.811). A significant amplification of N2 was found for Short over Long Delay (p=.028; F=5.326). Importantly, N2 trough correlated with d' specifically for Short A-PostB cues, such that a more negative N2 deflection indicated higher response sensitivity in the subsequent probe response (r^2=-.489).

Peak P3 amplitudes were measured at central-parietal electrode Pz (Kayser & Tenke, 2015). No main effects of Cue Type or Delay Length, nor interactions between Cue Type and Delay Length were observed.

As EEG activity is typically no longer phase locked after ~200 or 250 ms post-stimulus, time-frequency analyses were conducted for late components. Time-frequency results for delta, theta, and alpha are summarized in Table 5. Critically, late delta power (400:700 ms) was increased during Long delay at electrode CPz, and this increased activation was positively correlated with summary behavioral metric BSI-ER, selectively for Long delay BSI (LA r=.375; LB r=.367) (Figure 9). Further, theta power at left frontal FC3 (200:600 ms), a probable site for verbal working memory maintenance (Reuter-Lorenz et al., 2000) was selectively (positively) correlated with Long B d' (r^2=.307). Mid-frontal theta at FCz, involved in signaling the need for cognitive control (Cavanagh & Frank, 2014), was selectively predictive of Short Delay d' scores, with theta power (100:500 ms) positively correlated with Short B d' (r^2=.307) and theta phase consistency (100:500 ms) positively correlated with Short A d' (r^2=.499) and Short B d' (r^2=.499).

Table 4. ERP Components of Interest, Effects of Delay and Delay x Cue Interaction, and Peak Amplitude Correlations with Summary Behavioral Metrics

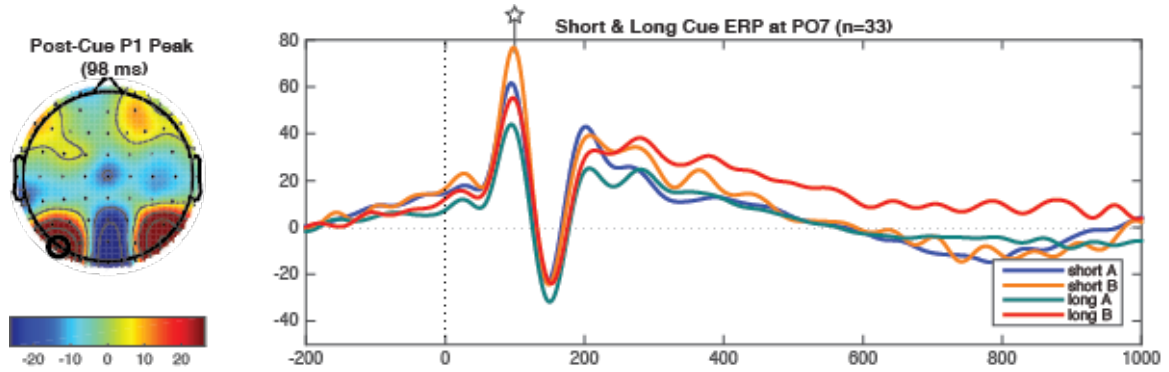| Comp	Eloc	A vs B	Delay	Cue*Delay	BSI:ER	d'	Beta	C
P1	PO3	n.s.	P=.008; F=8.125	n.s.	SA=.043; SB=.017; LA=-.228; LB=-.300;	SA=.234; SB=.171; LA=.339; LB=.086;	n.s.	SA=.205; SB=.228; LA=.023; LB=-.308
P1	PO4	n.s.	n.s.	n.s.	SA=-.019; SB=-.017; LA=-.209; LB=-.320;	n.s.	n.s.	n.s.
P1	PO7	P=.001; F=12.711	P<.001; F=15.748	n.s.	n.s.	SA =.158; SB =.144; LA = .596; LB = .345;		
P1	PO8	P=.026; F=5.457	P=.004; F=9.899	P=.076 # F=3.372	n.s.	n.s.	n.s.	n.s.
N1	POz	n.s.	n.s.	P=.091; # F=3.040	n.s.	n.s.	n.s.	SA =-.141; SB =-.064 LA =-.347; LB = .001;
P2	FCz	n.s.	P=.002; F=11.066;	n.s.	n.s.	n.s.	n.s.	n.s.
N2	AFz	P=.084; # F=3.181	P=.004; F=9.664	P=.019; F=6.105	n.s.	n.s.	n.s.	n.s.
P3	Pz	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Figure 5. PO7 ERP and P100 Topoplot

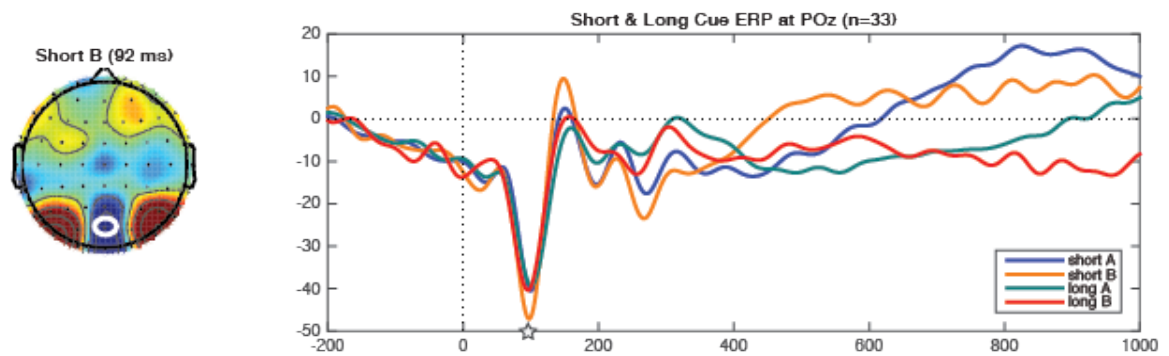**Figure 6.** POz ERP and N100 Topoplot

Table 5. Time-Frequency Frequencies of Interest, Effects of Delay and Delay x Cue Interaction, and Average Power Correlations with Summary Behavioral Metrics

Comp	Eloc (time)	Delay	Cue * Delay	BSI : ER	d'	Beta	C
Delta Power	AFz (250-500 ms)	P<.05; F=6.883	n.s.	SA: r=.366; SB: r=.330	LA: r=.395	SA:r=-.492	n.s.
Delta Power	CPz (300:700)	n.s.	n.s.	LA: r=.375; LB: r=.367	n.s.	n.s.	n.s.
Theta Power	FC3 (200:600)	n.s.	n.s.	LB:r=.375	LB: r=.307	n.s.	n.s.
Theta Power	FCz (100:500)	n.s.	n.s.	n.s.	SB: r=.437	SB: r=.542	n.s.
Theta Phase	FCz (100:500)	n.s.	n.s.	SA:r=.499; SB: r=.413;	n.s.	n.s.	n.s.
Alpha Power	AFz	P<.05; F=4.092	n.s.	n.s.	n.s.	SA: r=-.327	n.s.
Alpha Power	FC4	n.s.	n.s.	n.s.	LB: r=.478	SB: r=-.360	SB: r=-.328

Figure 7. P200 Topoplots

Short + Long P2 Topos (n=33)

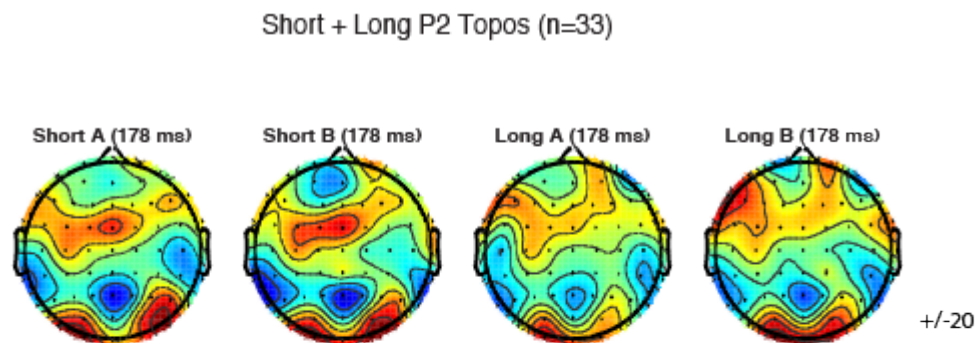Short A (178 ms)   Short B (178 ms)   Long A (178 ms)   Long B (178 ms)

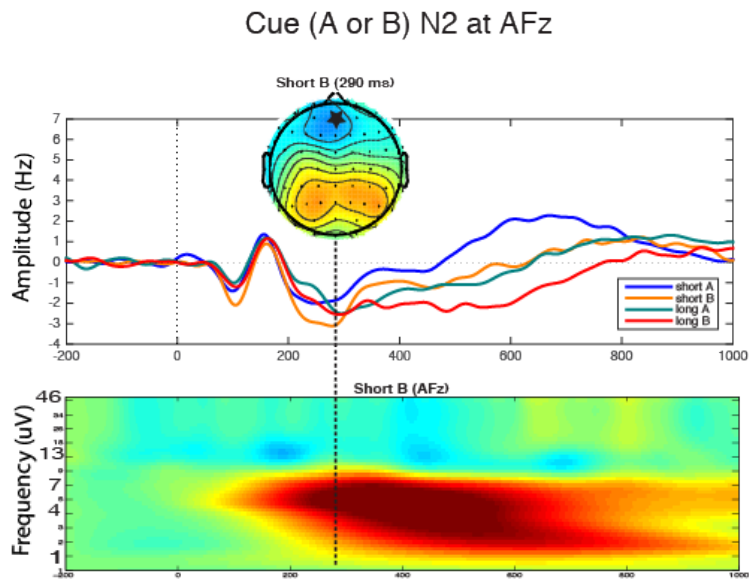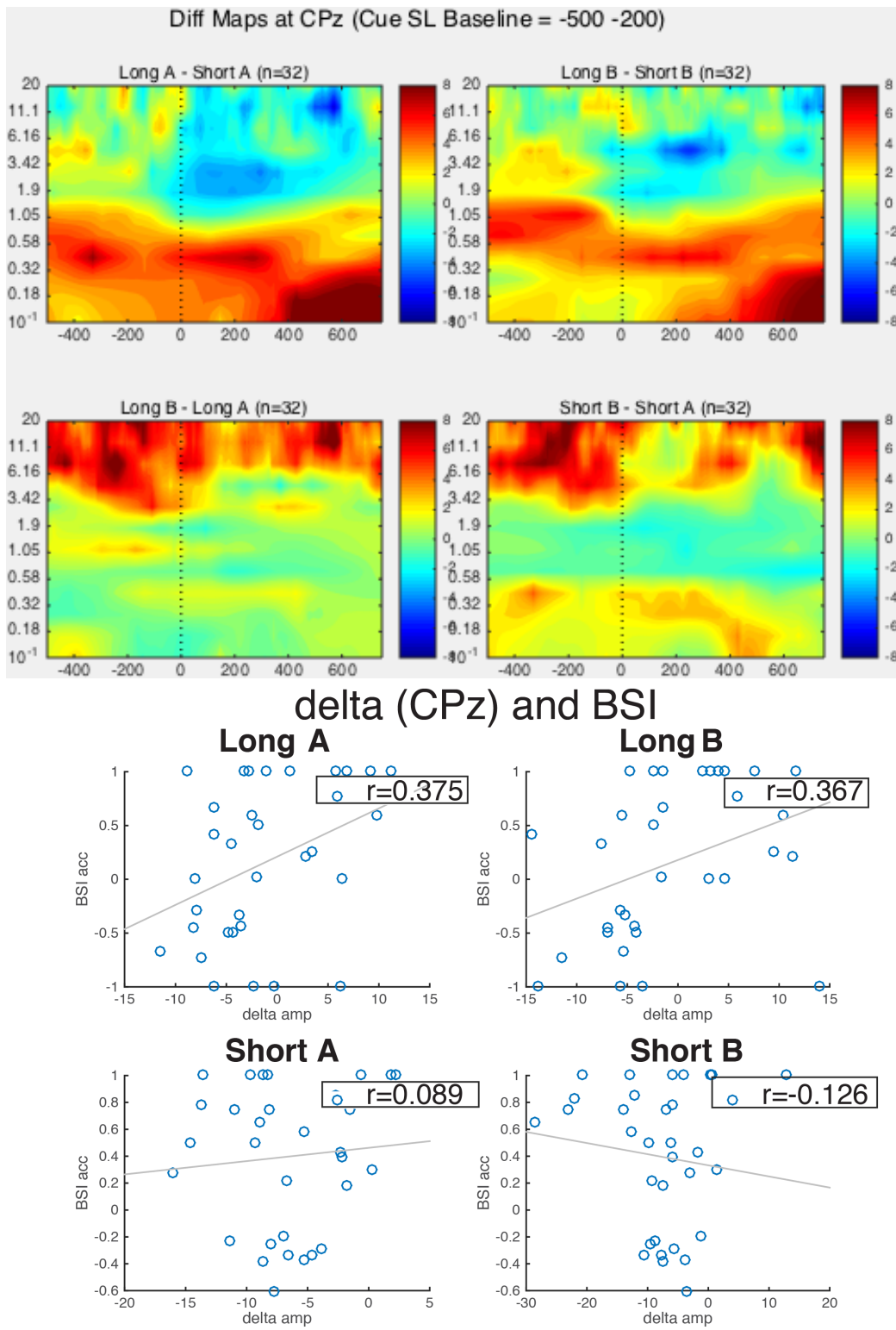+/-20

Figure 8. N2 at AFz

Figure 9. Late Delta Power at CPz and Correlations with BSI-ER

DISCUSSION

The present study sought to investigate differences in the AX-CPT task across short and long cue-probe delay lengths, to determine whether distinct types of proactive control are utilized based on delay length. In a within-subjects design, we experimentally manipulated the cue-probe delay duration between experimental blocks, igniting differences in control instantiation between known temporal delays. Accuracy and behavioral metrics were utilized to compare decision dynamics on trials demanding different types of control. EEG during the cue-probe delay was used to assess neural signatures of task switching and working memory, to parse activity underlying different instantiations of proactive control. Three major findings emerged from this study. First, accuracy to rare aY probes was selectively impaired during Short Delay, implicating specific short-delay difficulty in inhibiting a pre-potent aX response. Signal detection metrics provided further support for a delay-specific difference in response selection, as response sensitivity (d') was lower and decision criterion (C) was more liberal for aY probes in Short delay. Second, we observed significant differences in ERP signatures of attention, task-switching, and cognitive control based on delay length and cue type. Further, P2 amplitude at FCz correlated with Behavioral Shift Index in Short, but not Long delay, indicating a dissociable neural element that may distinguish a "task-switching" type of proactive control. Finally, late activity in delta at CPz selectively predicted Behavioral Shift Index in Long, but not Short delay, further dissociating a different type of "working memory maintenance" proactive control. This is the first study to attempt to dissociate different types of proactive control, and we find that different cue-probe delay lengths evoke neural signatures similar to "task switching" or

"working memory" that can be doubly dissociated to reveal distinct underlying proactive processes during the cue-probe delay.

Two sets of task-switching events took place in this experiment: rare "B" cues requiring a task-switch from the predominant "A" task set, and "A post-B" cues necessitating a switch back from the "B" rule trial to the "A" rule. Specifically in Short delay blocks, both of these task-switching events demonstrated a pattern of neural activity distinguishable from task-maintenance "A" and "A post-A" trials. Due to its specificity to task-switch trials and Short-delay context, this post-cue neural activity can be characterized as a delay-specific marker of task-switching (Cacioppo & Tassinary, 1990).

Behavioral differences by Delay Length

Accuracy was impaired specifically to rare aY probes in the *Short* CPD condition (Table 2 and Figure 2). This finding not only indicates difficulty in inhibiting the aX response that is demanded on 80% of A trials, but highlights that this pre-potency is significantly stronger and/or more difficult to overcome with a Short CPD. There was no interaction between Probe Type and Delay Length for Reaction Time, providing evidence that the aY accuracy differences by delay length were not due to a speed-accuracy trade-off.

Signal detection d', indicating response sensitivity, was decreased specifically to aY probes during *Short* delay. Response criterion measure C, which indexes one's tendency to respond more liberally (low C) or conservatively (high C) than the ideal response pattern, was significantly lower for aY probes in Short delay, revealing a more

liberal response criterion with rapid CPD. In contrast, no delay-related changes in d' or C were found for control-demanding bX probes.

This pattern of behavioral results seems to suggest that cue-probe delay changes specifically alter one's accuracy to responding to a rare probe after a common cue (aY), with rapid cue-probe delay associated with impaired inhibition of the pre-potent response.

Dissociating Proactive Control

For about the last decade, the Dual Mechanisms of Control framework has divided cognitive control into proactive and reactive cognitive control (T. S. Braver, 2012), with proactive control instantiated to actively maintain relevant goal-relevant information ahead of cognitively demanding events (Miller & Cohen, 2001), and reactive control called upon as a 'late correction' mechanisms utilized as needed, and only after a high-interference event occurs (Jacoby et al., 1999). Proactive control has been described and explored as a unitary construct, but this present work attempts to highlight how different types of proactive control are utilized based on known temporal differences as to when the cognitively demanding event will occur.

In the current study, EEG activity was analyzed during the cue-probe delay to reveal how cues were processed to proactively (ahead of the probe) instantiate cognitive control. If there are dissociable neural processes underlying different types of control instantiation ("A" vs "B" rules) during different known delay durations, one can argue

that participants are using different "types" of proactive control according to temporal

demands.

Dissociating Proactive Control: "Task-Switching" Type

We expected Short Delay cues to evoke a rapid, task-switching type of cognitive

control to "B" cues, for which control is needed to alter task goals. Neural differences

were observed for Short B vs. Long B cues in early sensory components (P100 and

N100), evaluative components (P200), and later preparatory components (P300, delta).

Critically, the Behavioral Shift Index (BSI-ER), widely used to differentiate between (a

unitary) proactive and reactive control, was strongly correlated with mid-frontal P200

neural activity only during Short Delay, indicating that Short Delay evokes neural

markers of proactive control that are separable from those evoked during Long Delay.

Similar dissociations in neural activity with BSI-ER were also found in antero-central

AFz delta activation (250-500 ms), which carried significant predictive power for BSI

ratio only in Short Delay.

Dissociating Proactive Control: "Working Memory Maintenance" Type

Instantiation of proactive control during the Long Delay was uniquely

characterized by an increase in late (400-1000 ms) centro-parietal (CPz) delta power,

with delta power positively correlated with BSI-ER only in Long Delay.   Recent

research suggests that sustained delta power increases may be important for maintaining

internal representations, and limiting extraneous sensory input (Harmony, 2013). Further

dissociation of Long delay performance, specific to rare "B" cues, is found in theta power at left fronto-parietal FC3.

Limitations and Future Directions

   The current study has several limitations, each of which invite questions to be addressed by future research. First, this study used assessed two cue-probe delay lengths: 1000 ms and 3000 +/- 500 ms. Although a 1000 ms CPD is commonly used in AX-CPT studies, the next most common CPD frequency is between 4500 and 6000 ms (Figure S1). It is unclear whether delay-related differences in control instantiation would change significantly with an increase in CPD from ie: 3 to 5 seconds; future studies should explore the full range of AX delay lengths used (500 ms :10,000 ms). In addition, this study's Short CPD was fixed at 1000 ms, while the Long CPD was jittered between 2500 and 3500 ms, introducing confounds of expectancy/surprise with delay duration. These parameters were set in the present experiment in order to maximize the chance of generating a maximal pre-potent response in the Short delay, but future investigations should systematically match temporal jitters between delay lengths.

   With the current set-up of this AX-CPT task, remembering "A" or "B" cue identity and rule involves a relatively low working memory load, especially for our sample of healthy college students. It is unclear how proactive control instantiation might differ with greater WM demands, as in the AX derivative Dot Pattern Expectancy (DPX) (Henderson et al., 2012; A. W. MacDonald et al., 2005; Otto, Skatova, Madlon-kay, & Daw, 2015) or 1-2-AX tasks (Hazy, Frank, & O'reilly, 2007). To begin to resolve

these questions, we are currently running a follow-up study on the WM-intensive DPX task, again contrasting Short and Long cue-probe delays.

One other potential confound in using the AX-CPT task to study control instantiation is that "B" cues predict with 100% certainty that the upcoming probe response will be "Left". CPD cognitive control activity evoked by "B" may be difficult to fully disentangle from activity in preparing a motor response.

Finally, the present study revealed a wide range of behavioral performance trends, especially for control-demanding aY and bX cues. With our limited number of participants (n=35), we were not sufficiently powered to analyze our data by between-subject trait differences in ie: impulsivity or planning. Future analyses should attempt to explore how individual differences modulate cognitive control instantiation over different temporal delays.

CONCLUSIONS

Overall, we find that altering the cue-probe delay length in the AX-CPT evokes instantiation of dissociable behavioral and neural signatures of proactive control. This double dissociation of two types of proactive control merits further critical discussion of the common conceptualization of proactive control as a unitary construct. These results also highlight the importance of delay length parameters in this common cognitive control task, and seem to demand that AX-CPT no longer be considered a unitary task across timing parameters.

Figure S1. Frequency of AX-CPT Cue-Probe Delay Durations Utilized in the AX-CPT

Literature

Figure S2. AX-CPT Task Design
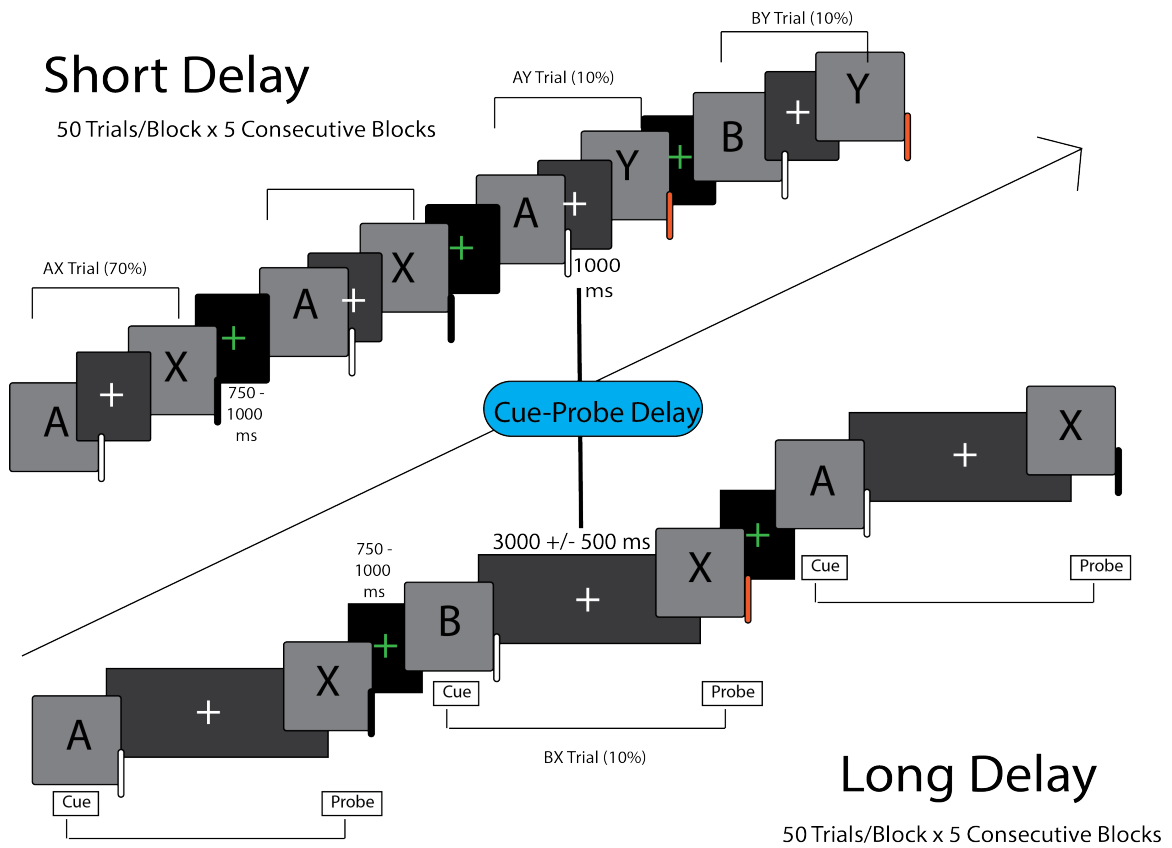
REFERENCES

Abdi, H. (1966). Signal Detection Theory (SDT), 1–9.

Astle, D. E., Jackson, G. M., & Swainson, R. (2006). Dissociating neural indices of dynamic cognitive control in advance task-set preparation: An ERP study of task switching. *Brain Research*, *1125*(1), 94–103. doi:10.1016/j.brainres.2006.09.092

Astle, D. E., Jackson, G. M., & Swainson, R. (2008). Fractionating the cognitive control required to bring about a change in task: a dense-sensor event-related potential study. *Journal of Cognitive Neuroscience*, *20*(2), 255–267. doi:10.1162/jocn.2008.20015

Barch, D. M., Berman, M. G., Engle, R., Jones, J. H., Jonides, J., MacDonald, A., … Sponheim, S. R. (2009). CNTRICS final task selection: Working memory. *Schizophrenia Bulletin*, *35*(1), 136–152. doi:10.1093/schbul/sbn153

Barch, D. M., Braver, T. S., Nystrom, L. E., Forman, S. D., Noll, D. C., & Cohen, J. D. (1997). Dissociating working memory from task difficulty in human prefrontal cortex. *Neuropsychologia*, *35*(10), 1373–80. doi:S0028393297000729 [pii]

Beste, C., Domschke, K., Radenz, B., Falkenstein, M., & Konrad, C. (2011). The functional 5-HT1A receptor polymorphism affects response inhibition processes in a context-dependent manner. *Neuropsychologia*, *49*(9), 2664–2672. doi:10.1016/j.neuropsychologia.2011.05.014

Bickel, S., Dias, E. C., Epstein, M. L., & Javitt, D. C. (2012). Expectancy-related modulations of neural oscillations in continuous performance tasks. *NeuroImage*, *62*(3), 1867–76. doi:10.1016/j.neuroimage.2012.06.009

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652. doi:10.1037/0033-295X.108.3.624

Brambilla, P., Macdonald 3rd, A. W., Sassi, R. B., Johnson, M. K., Mallinger, A. G., Carter, C. S., & Soares, J. C. (2007). Context processing performance in bipolar disorder patients. *Bipolar Disorders*, *9*(3), 230–237.

Brass, M., & von Cramon, D. Y. (2002). The role of the frontal cortex in task preparation. *Cerebral Cortex (New York, N.Y. : 1991)*, *12*(9), 908–914. doi:10.1093/cercor/12.9.908

Braver, T., Barch, D., & Cohen, J. (1999). Mechanisms of cognitive control: Active memory, inhibition, and the prefrontal cortex. *Pittsburgh (PA): Carnegie Mellon ….*

Retrieved from
ftp://46.13.242.59/IMATION_HDD/Documents/Work/Archives/2008/CIANS2008/
2nd set/literatura/var/COGNITIVNI_FUNKCE.PDF

Braver, T., & Cohen, J. (2001). Working memory, cognitive control, and the prefrontal
cortex: Computational and empirical studies. *Cognitive Processing*, *2*(1), 2555.
Retrieved from
file://localhost/Volumes/Volume_2/ZoteroLib_LV/library/Papers/2001/Braver/Cogn
itive Processing 2001 Braver.pdf

Braver, T. S. (2012). The variable nature of cognitive control: A dual mechanisms
framework. *Trends in Cognitive Sciences*, *16*(2), 106–113.
doi:10.1016/j.tics.2011.12.010

Braver, T. S., Paxton, J. L., Locke, H. S., & Barch, D. M. (2009). Flexible neural
mechanisms of cognitive control within human prefrontal cortex. *Proceedings of the
National Academy of Sciences of the United States of America*, *106*(15), 7351–7356.
doi:10.1073/pnas.0808187106

Braver, T. S., Satpute, A. B., Rush, B. K., Racine, C. a, & Barch, D. M. (2005). Context
processing and context maintenance in healthy aging and early stage dementia of the
Alzheimer's type. *Psychology and Aging*, *20*(1), 33–46. doi:10.1037/0882-
7974.20.1.33

Cacioppo, J. T., & Tassinary, L. G. (1990). Inferring psychological significance from
physiological signals. *The American Psychologist*, *45*(1), 16–28. doi:10.1037/0003-
066X.45.1.16

Carter, C. S., Braver, T. S., Barch, D. M., Botvinick, M. M., Noll, D., & Cohen, J. D.
(1998). Anterior cingulate cortex, error detection, and the online monitoring of
performance. *Science (New York, N.Y.)*, *280*(May), 747–749.
doi:10.1126/science.280.5364.747

Cavanagh, J. F., & Frank, M. J. (2014). Frontal theta as a mechanism for cognitive
control. *Trends in Cognitive Sciences*, *18*(8), 414–421.
doi:10.1016/j.tics.2014.04.012

Chung, Y. S., Mathews, J. R., & Barch, D. M. (2011). The effect of context processing on
different aspects of social cognition in schizophrenia. *Schizophrenia Bulletin*, *37*(5),
1048–56. doi:10.1093/schbul/sbq012

Cohen, J. D., Barch, D. M., Carter, C., & Servan-Schreiber, D. (1999). Context-
processing deficits in schizophrenia: converging evidence from three theoretically
motivated cognitive tasks. *Journal of Abnormal Psychology*, *108*(1), 120–133.

doi:10.1037/0021-843X.108.1.120

Cohen, J. D., Peristein, W. M., Braver, T. S., Nystrom, L. E., Noll, D. C., Jonides, J., & Smith, E. E. (1997). Temporal dynamics of brain activation during a working memory task. Nature Publishing Group.

Cohen, M. X. (2014a). *Analyzing Neural Time Series Data: Theory and Practice*. MIT Press. Retrieved from https://books.google.com/books?id=jTSkAgAAQBAJ

Cohen, M. X. (2014b). *Analyzing Neural Time Series Data: Theory and Practice*. MIT Press.

Crespo-Garcia, M., Pinal, D., Cantero, J. L., Diaz, F., Zurron, M., & Atienza, M. (2013). Working Memory Processes Are Mediated by Local and Long-range Synchronization of Alpha Oscillations. *Journal of Cognitive Neuroscience*, *25 (8)*(March), 1343–1357. doi:10.1162/jocn

D'Ardenne, K., & Eshel, N. (2012). Role of prefrontal cortex and the midbrain dopamine system in working memory updating. *Proceedings of the National Academy of Sciences*, *109*(49), 19900–19909. doi:10.1073/pnas.1116727109/-/DCSupplemental.www.pnas.org/cgi/doi/10.1073/pnas.1116727109

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. doi:10.1016/j.jneumeth.2003.10.009

Demiralp, T., Ademoglu, a, Schürmann, M., Başar-Eroglu, C., & Başar, E. (1999). Detection of P300 waves in single trials by the wavelet transform (WT). *Brain and Language*, *66*(1), 108–128. doi:10.1006/brln.1998.2027

Dias, E. C., Foxe, J. J., & Javitt, D. C. (2003). Changing plans: A high density electrical mapping study of cortical control. *Cerebral Cortex*, *13*(7), 701–715. doi:10.1093/cercor/13.7.701

Edwards, B. G., Barch, D. M., & Braver, T. S. (2010). Improving prefrontal cortex function in schizophrenia through focused training of cognitive control. *Frontiers in Human Neuroscience*, *4*(April), 32. doi:10.3389/fnhum.2010.00032

Hämmerer, D., Li, S. C., Müller, V., & Lindenberger, U. (2010). An electrophysiological study of response conflict processing across the lifespan: Assessing the roles of conflict monitoring, cue utilization, response anticipation, and response suppression. *Neuropsychologia*, *48*(11), 3305–3316. doi:10.1016/j.neuropsychologia.2010.07.014

Harmony, T. (2013). The functional significance of delta oscillations in cognitive processing. *Frontiers in Integrative Neuroscience*, *7*(December), 83.

doi:10.3389/fnint.2013.00083

Hazy, T. E., Frank, M. J., & O'reilly, R. C. (2007). Towards an executive without a homunculus: computational models of the prefrontal cortex/basal ganglia system. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *362*(1485), 1601–13. doi:10.1098/rstb.2007.2055

Henderson, D., Poppe, A. B., Barch, D. M., Carter, C. S., Gold, J. M., Ragland, J. D., … MacDonald, A. W. (2012). Optimization of a goal maintenance task for use in clinical applications. *Schizophrenia Bulletin*, *38*(1), 104–13. doi:10.1093/schbul/sbr172

Herrmann, C. S., Grigutsch, M., & Busch, N. a. (1999). EEG oscillations and wavealet analysis, (1929), 1–39.

Javitt, D. C., Shelley, a M., Silipo, G., & Lieberman, J. a. (2000). Deficits in auditory and visual context-dependent processing in schizophrenia: defining the pattern. *Archives of General Psychiatry*, *57*(12), 1131–1137. doi:10.1001/archpsyc.57.12.1131

Karayanidis, F., Coltheart, M., Michie, P. T., & Murphy, K. (2003). Electrophysiological correlates of anticipatory and poststimulus components of task switching. *Psychophysiology*, *40*(3), 329–348. doi:10.1111/1469-8986.00037

Karayanidis, F., Jamadar, S., Ruge, H., Phillips, N., Heathcote, A., & Forstmann, B. U. (2010). Advance preparation in task-switching: converging evidence from behavioral, brain activation, and model-based approaches. *Frontiers in Psychology*, *1*(July), 25. doi:10.3389/fpsyg.2010.00025

Karayanidis, F., Mansfield, E. L., Galloway, K. L., Smith, J. L., Provost, A., & Heathcote, A. (2009). Anticipatory reconfiguration elicited by fully and partially informative cues that validly predict a switch in task. *Cognitive, Affective & Behavioral Neuroscience*, *9*(2), 202–15. doi:10.3758/CABN.9.2.202

Kayser, J., & Tenke, C. E. (2006). Principal components analysis of Laplacian waveforms as a generic method for identifying ERP generator patterns: II. Adequacy of low-density estimates. *Clinical Neurophysiology*, *117*(2), 369–380. doi:10.1016/j.clinph.2005.08.033

Kayser, J., & Tenke, C. E. (2015). Issues and considerations for using the scalp surface Laplacian in EEG/ERP research: A tutorial review. *International Journal of Psychophysiology : Official Journal of the International Organization of Psychophysiology*, *97*(3), 189–209. doi:10.1016/j.ijpsycho.2015.04.012

Kerns, J. G., Cohen, J. D., MacDonald, A. W., Cho, R. Y., Stenger, V. A., & Carter, C. S.

(2004). Anterior cingulate conflict monitoring and adjustments in control. *Science (New York, N.Y.)*, *303*(5660), 1023–1026. doi:10.1126/science.1089910

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching--a review. *Psychological Bulletin*, *136*(5), 849–874. doi:10.1037/a0019842

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition-timing hypothesis. *Brain Research Reviews*, *53*(1), 63–88. doi:10.1016/j.brainresrev.2006.06.003

Lavric, A., Mizon, G. a., & Monsell, S. (2008). Neurophysiological signature of effective anticipatory task-set control: A task-switching investigation. *European Journal of Neuroscience*, *28*(5), 1016–1029. doi:10.1111/j.1460-9568.2008.06372.x

Leary, D. S. O., Turner, B. M., & Andreasen, N. C. (2003). CEREBELLAR TIMING DEFICITS IN SCHIZOPHRENIA International Congress on Schizophrenia Research 2003, 2003.

Lorsbach, T. C., & Reimer, J. F. (2010). Developmental Differences in Cognitive Control: Goal Representation and Maintenance During a Continuous Performance Task. *Journal of Cognition and Development*, *11*(2), 185–216. doi:10.1080/15248371003699936

Lucenet, J., & Blaye, A. (2014). Age-related changes in the temporal dynamics of executive control: a study in 5- and 6-year-old children. *Frontiers in Psychology*, *5*(July), 1–11. doi:10.3389/fpsyg.2014.00831

MacDonald, a W., Cohen, J. D., Stenger, V. a, & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science (New York, N.Y.)*, *288*(5472), 1835–1838. doi:10.1126/science.288.5472.1835

MacDonald, A. W., Goghari, V. M., Hicks, B. M., Flory, J. D., Carter, C. S., & Manuck, S. B. (2005). A convergent-divergent approach to context processing, general intellectual functioning, and the genetic liability to schizophrenia. *Neuropsychology*, *19*(6), 814–821. doi:10.1037/0894-4105.19.6.814

McAdam, D. W., Knott, J. R., & Rebert, C. S. (1969). Cortical slow potential changes in man related to interstimulus intevval and to pre-trial prediction of interstimulus interval. *Psychophysiology*, *5*(4), 349–358.

Meiran, N., Chorev, Z., & Sapir, a. (2000). Component processes in task switching. *Cognitive Psychology*, *41*(3), 211–253. doi:10.1006/cogp.2000.0736

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

Morales, J., Yudes, C., Gómez-Ariza, C. J., & Bajo, M. T. (2014). Bilingualism modulates dual mechanisms of cognitive control: Evidence from ERPs. *Neuropsychologia*, *66*, 157–169. doi:10.1016/j.neuropsychologia.2014.11.014

Nicholson, R., Karayanidis, F., Poboka, D., Heathcote, A., & Michie, P. T. (2005). Electrophysiological correlates of anticipatory task-switching processes. *Psychophysiology*, *42*(5), 540–54. doi:10.1111/j.1469-8986.2005.00350.x

Nolan, H., Whelan, R., & Reilly, R. B. (2010). FASTER: Fully Automated Statistical Thresholding for EEG artifact Rejection. *Journal of Neuroscience Methods*, *192*(1), 152–162. doi:10.1016/j.jneumeth.2010.07.015

Otto, A. R., Skatova, A., Madlon-kay, S., & Daw, N. D. (2015). Cognitive Control Predicts Use of Model-based Reinforcement Learning. *Journal of Cognitive Neuroscience*, *27*(2), 319–333. doi:10.1162/jocn

Paxton, J. L., Barch, D. M., Racine, C. a, & Braver, T. S. (2008). Cognitive control, goal maintenance, and prefrontal function in healthy aging. *Cerebral Cortex (New York, N.Y. : 1991)*, *18*(5), 1010–28. doi:10.1093/cercor/bhm135

Paxton, J. L., Barch, D. M., Storandt, M., & Braver, T. S. (2006). Effects of environmental support and strategy training on older adults' use of context. *Psychology and Aging*, *21*(3), 499–509. doi:10.1037/0882-7974.21.3.499

Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*, *72*(2), 184–187. doi:10.1016/0013-4694(89)90180-6

Pesaran, B., Pezaris, J. S., Sahani, M., Mitra, P. P., & Andersen, R. a. (2002). Temporal structure in neuronal activity during working memory in macaque parietal cortex. *Nature Neuroscience*, *5*(8), 805–811. doi:10.1038/nn890

Raghavachari, S., Kahana, M. J., Rizzuto, D. S., Caplan, J. B., Kirschen, M. P., Bourgeois, B., … Lisman, J. E. (2001). Gating of human theta oscillations by a working memory task. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *21*(9), 3175–3183. doi:21/9/3175 [pii]

Redick, T. S., & Engle, R. W. (2011). Integrating working memory capacity and context-processing views of cognitive control. *Quarterly Journal of Experimental Psychology (2006)*, *64*(6), 1048–1055. doi:10.1080/17470218.2011.577226

Reuter-Lorenz, P. a, Jonides, J., Smith, E. E., Hartley, A., Miller, A., Marshuetz, C., &

Koeppe, R. a. (2000). Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. *Journal of Cognitive Neuroscience*, *12*(1), 174–187. doi:10.1162/089892900561814

Reynolds, J. R., O'Reilly, R. C., Cohen, J. D., & Braver, T. S. (2012). The function and organization of lateral prefrontal cortex: A test of competing hypotheses. *PLoS ONE*, *7*(2). doi:10.1371/journal.pone.0030284

Richard, A. E., Carter, C. S., Cohen, J. D., & Cho, R. Y. (2013). Persistence, diagnostic specificity and genetic liability for context-processing deficits in schizophrenia. *Schizophrenia Research*, *147*(1), 75–80. doi:10.1016/j.schres.2013.02.020

Roux, F., & Uhlhaas, P. J. (2014). Working memory and neural oscillations: Alpha-gamma versus theta-gamma codes for distinct WM information? *Trends in Cognitive Sciences*, *18*(1), 16–25. doi:10.1016/j.tics.2013.10.010

Rushworth, M. F. S., & Behrens, T. E. J. (2008). Choice, uncertainty and value in prefrontal and cingulate cortex. *Nature Neuroscience*, *11*(4), 389–397. doi:10.1038/nn2066

Rushworth, M. F. S., Hadland, K. a, Paus, T., & Sipila, P. K. (2002). Role of the human medial frontal cortex in task switching: a combined fMRI and TMS study. *Journal of Neurophysiology*, *87*(5), 2577–2592. doi:DOI 10.1152/jn.00812.2001

Rushworth, M. F. S., Passingham, R. E., & Nobre, a. C. (2005). Components of Attentional Set-switching. *Experimental Psychology (formerly "Zeitschrift Für Experimentelle Psychologie")*, *52*(2), 83–98. doi:10.1027/1618-3169.52.2.83

Schmitt, H., Wolff, M. C., Ferdinand, N. K., & Kray, J. (2014). Age Differences in the Processing of Context Information. *Journal of Psychophysiology*, *28*(3), 202–214. doi:10.1027/0269-8803/a000126

Shenhav, A., Botvinick, M., & Cohen, J. (2013). The expected value of control: An integrative theory of anterior cingulate cortex function. *Neuron*, *79*(2), 217–240. doi:10.1016/j.neuron.2013.07.007

Sohn, M.-H., Albert, M. V, Jung, K., Carter, C. S., & Anderson, J. R. (2007). Anticipation of conflict monitoring in the anterior cingulate cortex and the prefrontal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(25), 10330–10334. doi:10.1073/pnas.0703225104

Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods, Instruments, & Computers : A Journal of the Psychonomic Society, Inc*, *31*(1), 137–149. doi:10.3758/BF03207704

Steiger, J. H. (1980). Tests for comparing elements of a correlation matrix. *Psychological Bulletin*. doi:10.1037/0033-2909.87.2.245

Tekok-Kilic, a, Shucard, J. L., & Shucard, D. W. (2001). Stimulus modality and Go/NoGo effects on P3 during parallel visual and auditory continuous performance tasks. *Psychophysiology*, *38*(3), 578–589. doi:10.1017/S0048577201991279

van Wouwe, N. C., Band, G. P. H., & Ridderinkhof, K. R. (2011). Positive affect modulates flexibility and evaluative control. *Journal of Cognitive Neuroscience*, *23*(3), 524–39. doi:10.1162/jocn.2009.21380