# FACTOR ANALYSIS OF COGNITIVE CONTROL

by

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## Abstract

By

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The Dual Mechanisms of Cognitive Control (DMC) was proposed to describe two distinct and coexisting mechanisms for cognitive control: proactive control and reactive control (Braver, 2012; Braver, Gray, & Burgess, 2007). The DMC framework assumes that proactive control and reactive control are independent. Though some evidence has been found to support the independence of the DMC mechanisms, this idea has not been investigated using latent variable techniques. In this study, I examined four tasks that have been proposed to test the DMC. Factor analysis on eight markers (one proactive control marker and one reactive control marker from each task) was conducted to verify the factor components of these markers. Although results indicated that the two markers were dissociable in some tasks, the markers did not load on two independent components in the factor analysis. Further, reliability analyses suggest that the tasks typically associated with measuring the DMC may not produce reliable markers.

# 1 Introduction

## 1.1 Cognitive control

### 1.1.1 Overview of Cognitive Control

Cognitive control refers to the ability to regulate our behavior to conduct a particular task or achieve a specific goal (see Braver, 2012; Miller & Cohen, 2001). In order to achieve a specific goal, we utilize cognitive control to organize our behavior. For example, imagine that you are going to buy some oranges in a supermarket after work. Buying oranges is the goal of this task. After getting into the supermarket, you have to regulate your behavior to initiate the process of searching for the oranges. Cognitive control is the core ability for us to regulate our search behavior in this situation.

A variety of terms have been used to describe cognitive control, such as “executive control”, “effortful control,” “executive attention,” “controlled attention,” and “executive functioning.” Different descriptions have also been used to define cognitive control. For example, some researchers describe it as the ability to *regulate behavior to achieve a goal in the face of interference* (Kane & Engle, 2002); or the ability to *plan how to achieve the formulated goals and to regulate behavior to achieve these goals* (Kimberg, D’Esposito, & Farah, 1997). Despite different definitions for cognitive control, there is one

fundamental feature that is consistent in all definitions: the processes of cognitive control should always be controlled and non-automatic. That is, it does not refer to those automatic cognitive processes where a response is triggered without a need for conscious awareness or active control. Controlled processes are activated through conscious awareness (Schneider & Shiffrin, 1977).

### 1.1.2 Neural substrates

The substrates underlying cognitive control includes regions of the cingular cortex, the prefrontal cortex, and the dopaminergic system. Many findings support that idea that the prefrontal cortex is the center of cognitive control (e.g. Gazzaley & D'Esposito, 2007; Koechlin & Summerfield, 2007; Luria & Tsvetkova, 1964; Miller & Cohen, 2001; Stuss & Levine, 2002). Several lines of neuroimaging evidence converge on the conclusion that reliable activations in the prefrontal cortex have been found during tasks that demand cognitive control (e.g. Collette, Hogge, Salmon, & Von der Linden, 2006; Smith & Jonides, 1999). Similarly, studies on patients with a prefrontal lesion have found significant impairments of goal-driven behavior (e.g., Stuss & Levine, 2002). Kane and Engle (2002) found that the dorsolateral part of prefrontal cortex is especially involved in cognitive control.

### 1.1.3 The function of cognitive control

There are many accounts regarding the functions of cognitive control. For some accounts, cognitive control consists of several distinct functions. For example, Lezak (1982) proposed that cognitive control consists of four functions: formulating goals, planning actions for goals, conducting actions in practice, and applying actions effectively. As another example, Barkley (1997) proposed that cognitive control consists of four functions distinct from Lezak's (1982) model: self-regulation of motivation, emotion, and arousal; internalization of speech; analyzing and synthesizing a situation to generate new responses; and working memory. Other researchers have tried to propose an integrative conceptual framework of cognitive control rather than a collection of defined functions. For example, Gonthier (2014) proposed that cognitive control should refer to the non-automatic regulation of behavior according to a goal.

### 1.1.4 Top-down or bottom-up?

When do we utilize cognitive control to achieve our goals? There are two main situations. The first situation is when cognitive control is actively recruited in anticipation of an action, also called top-down situation. In this situation, an internal goal drive regulates our behavior (Miller & Cohen, 2001). The other situation is when cognitive control is triggered by signals in a bottom-up manner (Botvinick, Braver, Barch, Carter, & Cohen, 2001). In this situation, cognitive

control is not driven by internal goals, but by some feature of the situation. The evidence of the coexistence of “top-down” and “bottom-up” control is also reported in some studies (Braver, Gray, & Burgess, 2007; Desimone & Duncan, 1995).

## 1.2 The Dual Mechanisms of Cognitive Control

### 1.2.1 Overview of Dual Mechanisms of Cognitive Control

The Dual Mechanisms of Cognitive Control (DMC) was proposed to describe the two distinct and coexisting top-down and bottom-up mechanisms of cognitive control, termed proactive control and reactive control (Braver, 2012; Braver, Gray, & Burgess, 2007). The difference between the two mechanisms is how the goals of the tasks are activated and how actions are selected according to the goals.

Proactive control means that people actively maintain the goals until actions are required. People who engage in proactive control will prepare to regulate their behavior before the event occurs. Proactive control involves continuous control sustained throughout the task.

Reactive control means that people will activate the goals after they are triggered by environmental information. People who engage in reactive control

will not prepare to regulate behavior before the event occurs, instead, they will reactivate the goal for the task after receiving a stimulus and then initiate behavior regulation.

In the example mentioned earlier about buying oranges in a supermarket, people who engage in proactive control will keep this goal in mind. After getting into the supermarket, they will immediately start searching for oranges and actively remind themselves of the goals until they complete the task. By contrast, people who engage in reactive control will walk through the supermarket until they see oranges. At that point, they will reactivate the goal that they should buy oranges and will complete the task.

### 1.2.2 Benefits and Costs for DMC

The two control mechanisms have their own costs and benefits (Braver, Gray, & Burgess, 2007). Proactive control exhausts more cognitive resources, but is sensitive to contextual information required to implement control in advance, and so can help us to conduct the tasks more quickly. On the other hand, reactive control exhausts fewer cognitive resources because we do not have to keep the goal active, but reactive control slows our actions.

### 1.2.3 Evidence for DMC

A number of tasks have been used to investigate the DMC framework. Below, I describe four tasks and the evidence they have produced as evidence for DMC.

#### 1.2.3.1 The AX-Continuous Performance Task (AX-CPT)

The AX-CPT is an experimental paradigm that has been utilized in the majority of research designed to investigate the distinction of proactive and reactive control (see, e.g., Braver, 2012; Braver, Paxton, Locke, & Barch, 2009; Chatham, Frank, & Munakata, 2009). The AX-CPT requires subjects to respond to a letter probe after a letter cue. There are four types of trials: AX, AY, BX and BY trials (where A = 'A,' B = any letter other than 'A,' X = 'X,' and Y = any letter other than 'X'). Subjects are asked to respond 'target' when they see an "AX" pair, which means an 'A' cue is followed by an 'X' probe. Otherwise, they should respond 'non-target' to all other probes.

While several variations of this task have been used, it is common for AX and BY trials to be the most prevalent (e.g., 40% AX trials, 40% BY trials, 10% AY trials, and 10% BX trials). This is done so that after seeing an 'A' cue, participants expect an 'X' probe. Thus, if participants are engaging in proactive control, they should be prepared to respond 'target' after seeing an 'A' because

the majority of trials with an ‘A’ cue are AX trials. More specifically, they should be more likely to commit errors or have slower RTs when a letter other than ‘X’ follows an ‘A,’ that is, on AY trials. In contrast, if participants are engaging in reactive control, they should consider the goal following the probe. More specifically, they should be more likely to commit errors or have slower RTs when a letter other than ‘A’ precedes ‘X,’ that is, on BX trials.

A common marker of proactive control in this paradigm is the A-cue bias (sum of hits on AX trials and false alarm of AY trials). A common marker of reactive control in this paradigm is the difference in RTs between BX and BY trials. A study found that strategy training and no-go manipulations in AX-CPT induced proactive control and reactive control shifts using these markers, respectively (Gonthier, Macnamara, Chow, Conway, & Braver, 2016).

#### 1.2.3.2 Stroop Task with Proportion Congruency Effect

The Stroop task has also been used to test the existence of two distinct control mechanisms. Gonthier, Braver, and Bugg (2016) manipulated the proportion congruency in a picture-word Stroop task in which participants were asked to verbally name the pictures of animals while ignoring the words on the pictures. All participants engaged in three block types: List-Wide mostly congruent (LWmc), List-Wide mostly incongruent (LWmi), and Item-Specific (half the

items were mostly congruent and the other half were mostly incongruent, ISmc and ISmi). It is assumed that the difference in the Stroop effect that participants experience in mostly incongruent versus mostly congruent conditions can be viewed as the result of control demands, which is termed the proportion congruency (PC) effect. Gonthier and colleagues (2016) hypothesized that in the list-wide condition, the control demands are global (proactive) because the proportion of congruence is consistent, and thus preparation is useful, whereas in the item-specific condition, the control demands are local (reactive) because the proportion of congruence varies across trials. Gonthier et al. (2016) found that the proportion congruency effect in list-wide and item-specific conditions had a weak and negative correlation, meaning that those who have a larger reduction in Stroop effect due to the list-wide PC effect are less influenced by the item-specific PC effect. This result was interpreted as evidence that participants shifted toward proactive control in the list-wide condition, whereas they shifted toward reactive control in the item-specific condition. Thus, the two markers of proactive and reactive control in this task were the proportion congruency effect in the list-wide conditions and the congruency effect in the item-specific condition, respectively.

#### 1.2.3.3 Sternberg Working Memory Task with Recent-Negative Interference

There is evidence for the DMC in other paradigms as well. One such task is a working memory task with high interference probes in the form of recent negatives (D'Esposito & Postle, 1999). This task is based on the Sternberg working memory task, in which participants are asked to identify whether a probe word was a member of that trial's memory set. In the modified version used to investigate DMC, there are two conditions, high and low interference expectancy, which contain different proportions of recent negative trials in which the probe word of the trial was shown in the previous trial rather than in the current trial. Recent negative probes seldom occurred in the low expectancy condition, while recent negative probes occurred frequently in the high expectancy condition. It is assumed that in the high expectancy condition, participants are prepared to deal with the influence from recent negative stimulus (and thus engage in proactive control), while in the low expectancy condition, they are less prepared for the recent negative stimulus (and thus engage in reactive control). Burgess and Braver (2010) observed shifting temporal dynamics and specificity of lateral prefrontal cortex (PFC) activity according to the expectancy manipulation. In the low expectancy condition, a probe-triggered increase in activity was observed in left inferior PFC, especially on recent negative probe trials, which showed the recruitment of reactive control. However, in the high expectancy condition, an increase in lateral PFC

activity during the delay period was observed prior to probe onset, and this effect occurred on all trials (Burgess & Braver, 2010). While this was primarily a neuroimaging study, Burgess and Braver (2010) also found that there was greater interference (longer RTs) from negative probes in the low expectancy condition than in the high expectancy condition. Thus, the behavioral markers of proactive and reactive control in this task were negative probe trial RTs minus non-negative probe trial RTs in the high expectancy and low-expectancy conditions, respectively.

#### 1.2.3.4 Cued Task-Switching Paradigm

Another task used to demonstrate the DMC was the cued task-switching paradigm with motivational incentives. Motivational incentives were assumed to induce participants' proactive control in a task-switching paradigm, while participants are assumed to engage in reactive control when there is no incentive. Savine, Beck, Edwards, Chiew, and Braver (2010) found that the switch costs for reaction times in incentive trials were greater than in non-incentive trials. In addition, on trials with motivational incentives, an increase in activity was found, compared to no incentive trials, in left dorsolateral PFC suggesting a shift toward proactive control (Savine et al., 2010).

## 1.3 Present study

The DMC framework assumes proactive control and reactive control are two independent mechanisms. Despite there being some evidence that this is the case (e.g., Braver, 2012; Braver, et al., 2009), this idea has not been investigated using latent variable techniques. Indeed, latent variable analysis can provide evidence as to whether cognitive control constitutes two different processes, rather than two ends of a continuum, which would provide evidence for the DMC framework (Gonthier et al., 2016).

I have described four paradigms that have been used to test the DMC framework. For each paradigm, behavioral markers are proposed as indicators of proactive control and reactive control, respectively. Details of these markers are described in the Methods. See also Table 1.

In this study, these markers will be used in a factor analysis to examine whether performance on these measures represents two independent factors or a single factor. If all markers load on two latent components according to their proposed identities (proactive vs. reactive), it is an evidence to support the two independent mechanisms of cognitive control. In contrast, if all markers load on a single factor (with positive and negative signs depending on the marker type), it is evidence in support of a single mechanism of cognitive control.

Table 1

*Markers in Each Task for Proactive and Reactive Control*

| | Proactive control | Reactive control |
|---|---|---|
| AX-CPT | A-cue bias | BX – BY RT |
| Picture-Word Stroop Task | List-wide proportion congruency effect | Item-specific proportion congruency effect |
| Sternberg Working Memory Paradigm | Recent negative effect in high expectancy condition | Recent negative effect in low expectancy condition |
| Task-Switching Paradigm | Switch cost in cued condition | Switch cost in non-cue condition |

Note: We summarize the most typical markers here.

# 2 Method

## 2.1 Participants

This study was pre-registered on the Open Science Framework (https://osf.io/9pwbk/). According to the rule of 10, I should collect data at least 10 times the number of indices which is 8. However, for great power, I stopped data collection at the end of the weekend following the 100th participant for this thesis.

One hundred and four undergraduates from Case Western Reserve University participated in the study in exchange for partial course credit. Six (5.77% of the data) participants' data were excluded from analysis for the following reasons: One participant mapped wrong keys on the keyboard for a task; one participant quit the experiment because of falling asleep; and four participants had missing data in at least one block. The final number of participants was 98.

## 2.2 General Procedure

All participants completed the four tasks hypothesized to test the dual mechanisms of cognitive control. All tasks were designed in E-prime 2.0. Participants responded by pressing keys. Reaction time and accuracy were recorded for each response. The order of tasks was counterbalanced.

## 2.3 Tasks

### 2.3.1 AX-Continuous Performance Task (AX-CPT)

#### 2.3.1.1 AX-CPT Task Description

Participants were asked to respond 'target' when they saw the probe 'X' in an AX pair, otherwise, they were instructed to respond 'non-target' to any other letters. All participants experienced four types of trials in a random order. Each participant conducted three blocks. In total, there were 180 letter-pair trials that

required responses to probes and 36 no-go trials. In half the no-go trials, the cue is an ‘A’, and in the other half of no-go trials, the cue is a letter other than ‘A’. Among those trials needing responses for probes, the percentages of AX and BY trials were 40% each and the percentages of AY and BX trials were 10% each. Each trial began with a cue which was presented in the center of the screen for 500 ms followed by a 3500 ms delay. Then a probe was presented for 500 ms, and a 1000 ms inter-trial interval followed. Participants were required to respond to all stimuli. Responses were collected by pressing either a ‘non-target’ key with the index finger (for all cues and non-target probes) or a ‘target’ key with the middle finger (for target probes) on the keyboard. In order to avoid proactive biases in young adults, a small percentage of no-go trials were interspersed in the task (Gonthier et al., 2016). In no-go trials, the second letter was replaced with a digit and participants were asked to inhibit any response when they saw the digits. See Figure 1.

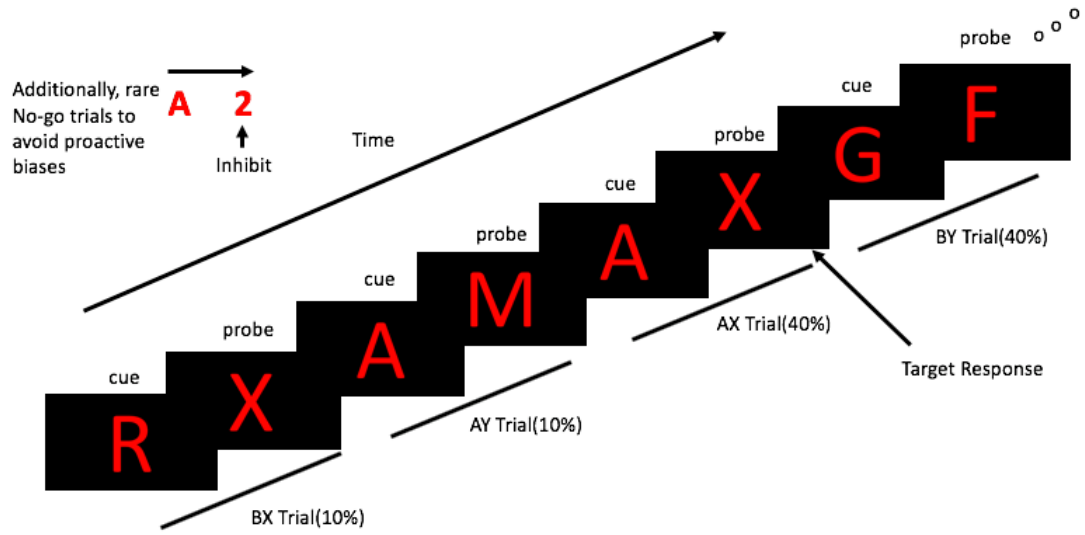


*Figure 1.* AX-CPT Paradigm.

#### 2.3.1.2 AX-CPT Markers

Following Braver's recommendations, in the AX-CPT, the marker for proactive control is the A-cue bias measure based on signal detection theory, calculated by the sum of AX hits and AY false alarms. It indicates the general tendency to make a target response following an A-cue. The marker for reactive control is the difference in reaction time between BX and BY trials, which indicates the independent slowing effect caused by the X probe.

### 2.3.2 Picture-Word Stroop Task

#### 2.3.2.1 Picture-Word Stroop Task Description

In the Picture-Word Stroop task, participants were asked to indicate the picture of the animals while ignoring the word on the picture, by pressing matching keys on the keyboard. There were four types of pictures of animals (bird, cat,

dog, and fish). Each of them could be matched with other words of animals for a total of 16 unique combinations. See Figure 2. In a counterbalanced order, all participants engaged in three blocks: a List-Wide mostly congruent (LWmc) block, a List-Wide mostly incongruent (LWmi) block, and an Item-Specific (half of the items were mostly congruent and the other half are mostly incongruent, ISmc and ISmi) block. In the LWmc block, the proportion of congruent trials was 75% and the proportion of incongruent trials was 25%. In the LWmi block, the proportion of congruent trials was 25% and the proportion of incongruent trials is 75%. In the Item-Specific block, two of the four animals were mostly congruent (75% of trials with these animals were congruent), and the other two animals were mostly incongruent (25% of trials are congruent). Participants conducted 288 trials in the LWmc block, 288 trials in the LWmi block, and 384 trials in the IS block (192 PC-75 trials and 192 PC-25 trials). Trials were separated by a 1000ms inter-trial interval, which began immediately after participants responded. The original study also included PC-50 trials (50% congruency proportion trials) with another four animals and words, which were added into all three blocks. I removed this trial type because 1) it did not contribute primary evidence for DMC, 2) so that participants only had four (rather than eight) keyboard responses, and 3) to avoid the fatigue effects given that participants were completing three additional tasks in this study.

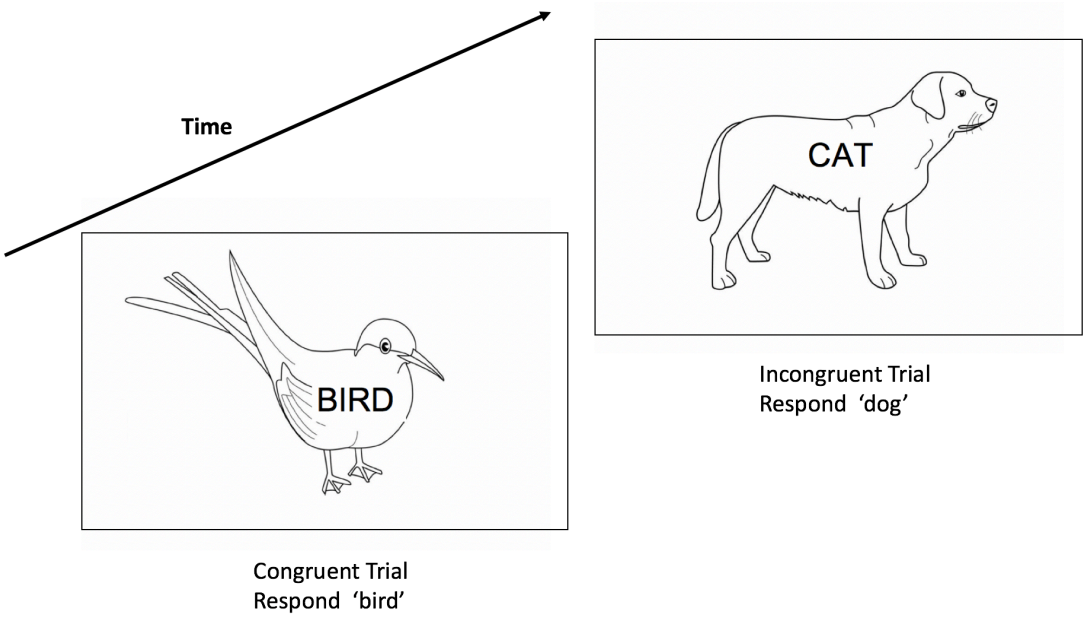


*Figure 2.* Picture-Word Stroop Task (Gonthier et al., 2016).

#### 2.3.2.2 Picture-Word Stroop Task Markers

As was the case in Gonthier et al. (2016), the marker of proactive control in the Picture-Stroop task is the proportion congruency effect in the list-wide condition. This is the difference of the Stroop effect (incongruent RTs minus congruent RTs) between LWmi and LWmc. The marker of reactive control is the proportion congruency effect in the item-specific condition. This is the difference of the Stroop effect between ISmi and ISmc.

### 2.3.3 Sternberg Working Memory task

#### 2.3.3.1 Sternberg Working Memory Task Description

In the Sternberg Working Memory task, participants viewed a list of five words followed by one probe word. All the words were one- or two- syllable nouns, the length of which were between 4 and 6 letters. Participants were asked to indicate whether the probe word appeared in that trial's memory set, by pressing either a 'non-target' key or a 'target' key on the keyboard. Each trial began by presenting a 5-word memory set for 2500ms, followed by a 5000ms delay. Then a probe appeared for 2000ms. The inter-trial interval was 1000ms. An equal number of positive and negative probes appeared in all four blocks. In some cases, the probe word appeared on the previous trial's list (i.e., a recent negative). In total, there were 80 trials in the high expectancy condition and 80 trials in the low expectancy condition. In the high expectancy condition (two blocks), the proportion of recency trials was 40% for both positive and negative. In the low expectancy condition (the other two blocks), the proportion of recency trials was 10% for both positive and negative. The two conditions were assigned in a counterbalanced order. See Figure 3.

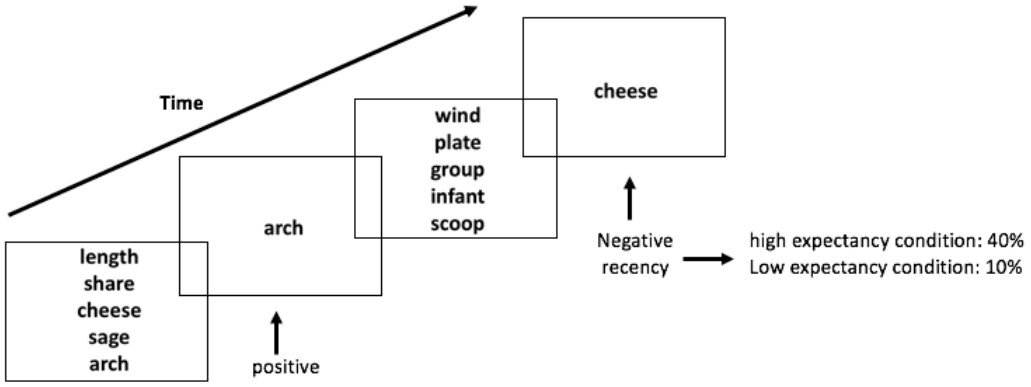


*Figure 3.* Sternberg Working Memory Paradigm.

#### 2.3.3.2 Sternberg Working Memory Task Markers

As in Burgess and Braver (2010), the marker for proactive control in the Sternberg Working Memory task is the recent negative interference in the high expectancy condition. This is the difference in reaction times between the recent negative trials and the novel negative trials in the high expectancy blocks. The marker for reactive control is the recent negative interference in the low expectancy condition. It is the difference in reaction times between the recent negative trials and the novel negative trials in the low expectancy blocks.

### 2.3.4 Task-Switching Task

#### 2.3.4.1 Task-Switching Task Description

In the Task-Switching Task, participants viewed a number in a 2 x 2 grid. If the number appeared in either of the upper two cells, participants we asked to indicate whether the number was odd or even; if the number appeared in either

of the lower two cells, participants were asked to indicate whether the number was larger than 5 or smaller than 5 (5 never appeared). Participants responded by pressing keys on the keyboard as shown in Figure 4. Participants performed 4 blocks, and each of them contain 41 trials, in which 20 of them were switched trials, 20 of them were non-switch trials and the first trial was a dummy trial. There were two conditions (each containing two blocks). In the cued condition, there was a 500ms cue that appeared before the stimulus indicating the location and thus the task type in each trial. In the non-cued condition, there was no cue before the stimulus. The inter-trial interval was 1000ms after the response was made. The conditions were assigned in a counterbalanced order.

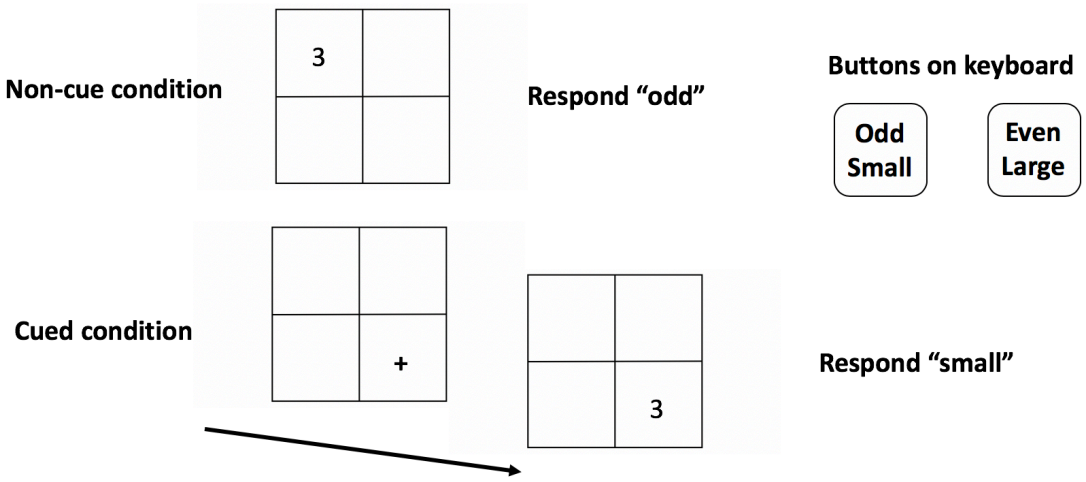


*Figure 4.* Task-Switching Paradigm.

#### 2.3.4.2 Task-Switching Task Markers

In the Task-Switching Task, the marker for proactive control is the switch cost (switch trial RTs minus non-switch trial RTs) in the cued condition, where participants have the opportunity to prepare for a response type. The marker for reactive control is the switch cost in the non-cued condition, where participants must react to the stimuli and its location to respond accurately.

# 3 Results

## 3.1 Results of Tasks

### 3.1.1 AX-CPT

#### 3.1.1.1 AX-CPT Reliability

Split-half reliability was assessed for every type of trial and each marker. Missing data were replaced with the mean. Spearman-Brown prediction formula was used as correction for split-half reliability (de Vet, Mokkink, Mosmuller, & Terwee, 2017). As can be seen in Figure 5, accuracy and RT reliability for frequent trial types (AX and BY) was acceptable. Reliability for relatively infrequent trial types (AY and BX) was low. The proactive and reactive markers, which include both frequent and infrequent trial types, were unreliable.

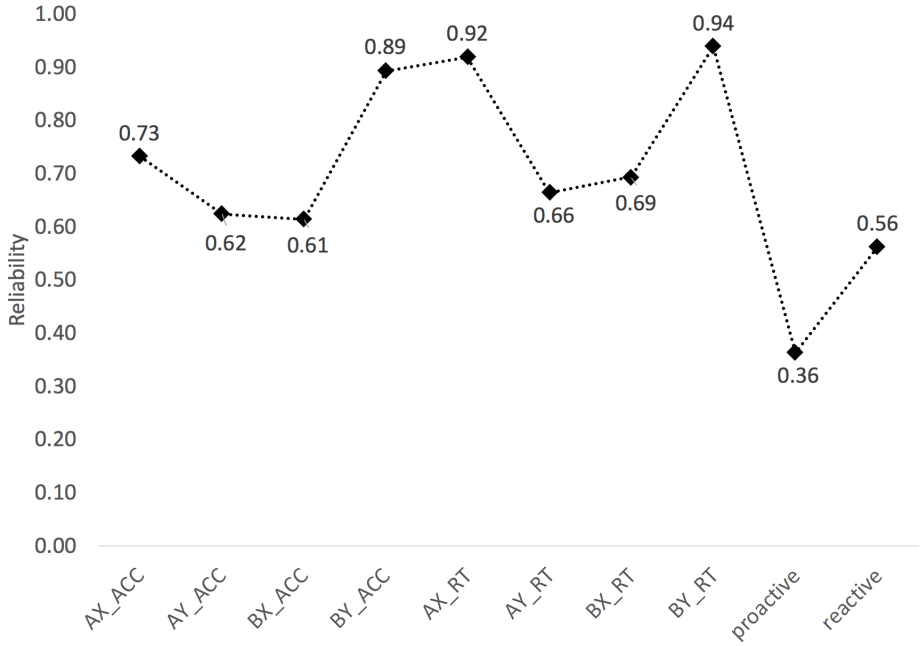


*Figure 5.* Reliability in AX-CPT. ACC: Accuracy; RT: Reaction Times.

### 3.1.1.2 AX-CPT Performance Results

Figure 6 displays the accuracy and RTs for correct trials by trial type. To be scored as accurate, both the cue and probe responses needed to be correct. The mean A-cue bias (AX hits + AY false alarms, i.e., the proactive marker) was 1.00 (*SD* = 0.11). The difference between reaction times of BX and BY trials (i.e., the reactive control marker) was significant, $t(97) = 5.073$, $p < .001$, $d = 0.512$. The correlation between the proactive and reactive markers was $r(98) = -.142$, $p = .164$.

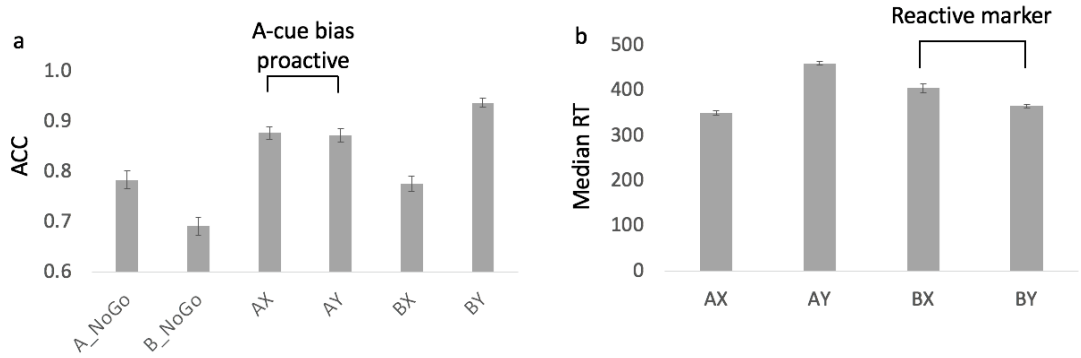


*Figure 6.* Performance for Each Trial Type in AX-CPT. A panel = accuracy results; A_NoGo: no-go trial with 'A' as the cue; B_NoGo: no-go trial with letter other than 'A' as the cue. b) panel = reaction time results.

## 3.1.2 Picture-Word Stroop Task

### 3.1.2.1 Picture-Word Stroop Task Reliability

Split-half reliability was assessed with Spearman-Brown correction for every type of trial, every congruency (Stroop) effect, and both markers in the Stroop task. Missing data were replaced with the mean. As can be seen in Figure 7, reliability for all trial types were high. However, reliability for the Stroop effect was unacceptably low. Additionally, the proactive and reactive markers, which include Stroop effects, were unreliable.

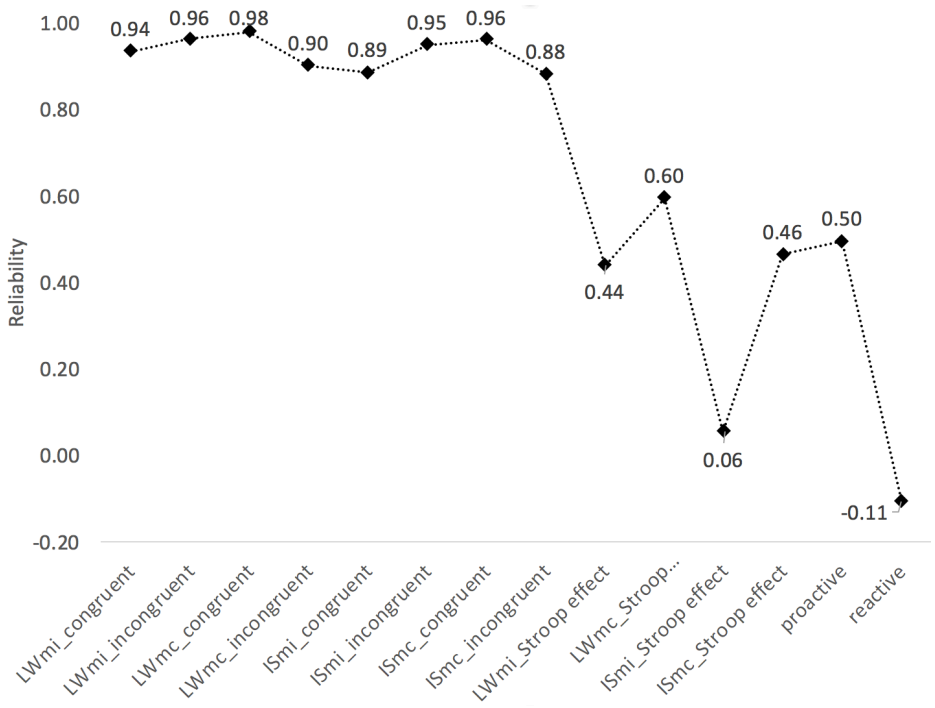


*Figure 7.* Reliability in Picture-Word Stroop Task.

### 3.1.2.2 Picture-Word Stroop Task Performance Results

RTs for correct trials are displayed in Figure 8. In the Picture-Word Stroop task, the Stroop effects were significant in the LWmi, LWmc, ISmi, and ISmc conditions, $t(97) = 7.562$, $p < .001$, $d = 0.764$; $t(97) = 9.704$, $p < .001$, $d = 0.980$; $t(97) = 6.108$, $p < .001$, $d = 0.617$; $t(97) = 7.955$, $p < .001$, $d = 0.804$, respectively. Furthermore, in list-wide conditions, the Stroop effect in the mostly incongruent condition was smaller than in the mostly congruent condition, $t(97) = -4.392$, $p < .001$, $d = -0.444$. The same proportion congruency effect was also found in the item-specific conditions, $t(97) = -3.327$, $p = .001$, $d = -0.336$. The correlation between proactive and reactive markers was $r(98) = -.218$, $p = .031$.

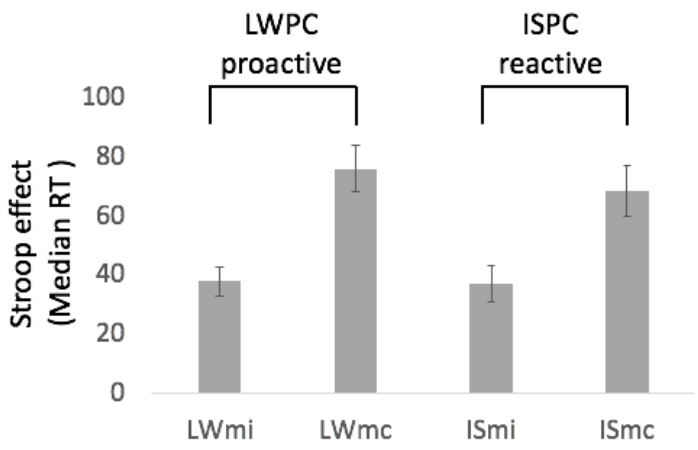


*Figure 8.* Performance in Picture-Word Stroop Task.

### 3.1.3 Sternberg Working Memory Task

#### 3.1.3.1 Sternberg Working Memory Task Reliability

Split-half reliability was assessed with Spearman-Brown correction for every type of trial and both markers. Missing data were replaced with the mean. As can be seen in Figure 9, reliability for frequent trial types was acceptable. The reliability of infrequent trial types (i.e., recency trials in the low expectancy conditions) was low. The proactive and reactive markers were unreliable.

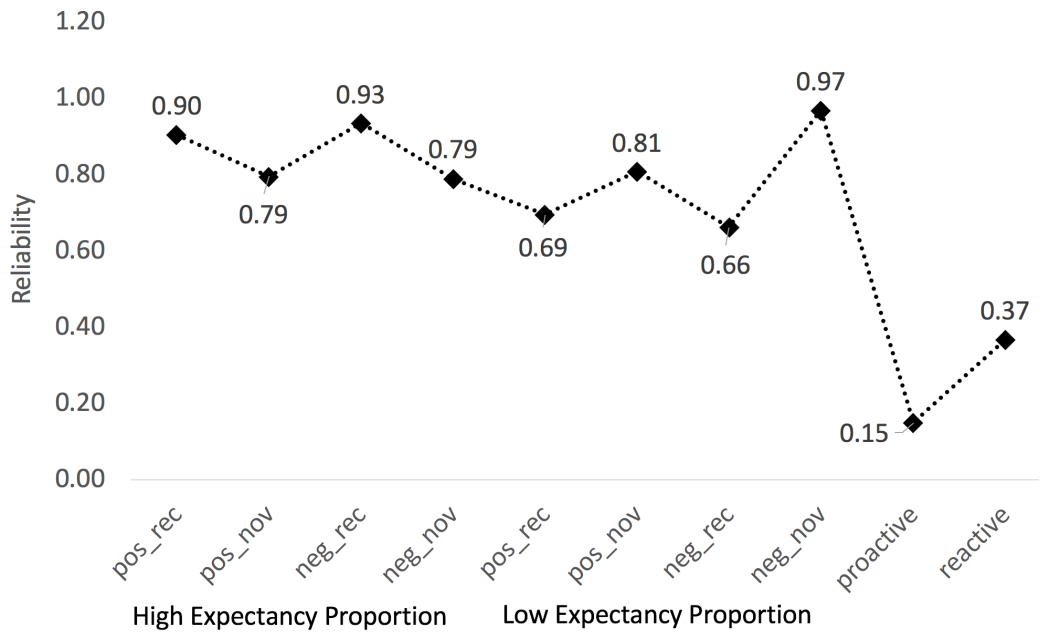


*Figure 9.* Reliability in Sternberg Working Memory Task. pos = positive; neg = negative; rec = recent; nov = novel.

### 3.1.3.2 Sternberg Working Memory Task Performance Results

In the Sternberg working memory task, RTs for correct trials are displayed in Figure 10. Participants' performance in negative-novel trials was better than that in negative-recent trials in the high expectancy condition, $t(97) = 8.398$, $p < .001$, $d = 0.848$. The same pattern was found in the low expectancy condition, $t(97) = 13.360$, $p < .001$, $d = 1.350$. This means that the Recent Negative Effect (RNE) was large and significant in both high and low expectancy conditions. See Figure 10. The correlation between the proactive and reactive markers was $r(98) = .222$, $p = .028$.

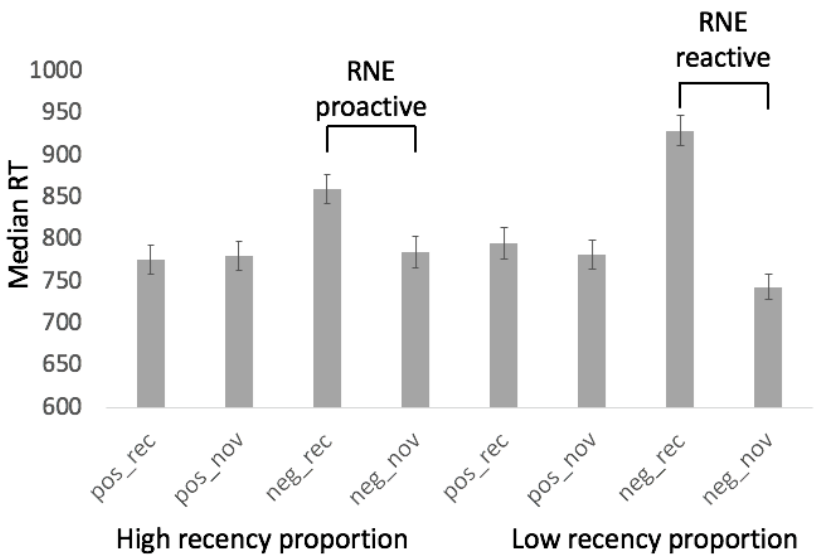


*Figure 10.* Performance in Sternberg Working Memory Task. pos = positive = neg = negative; rec = recent; nov = novel.

## 3.1.4 Task-Switching Task

### 3.1.4.1 Task-Switching Task Reliability

Split-half reliability was assessed with Spearman-Brown correction for all trial types and both markers. Missing data were replaced with the mean. As can be seen in Figure 11, reliability for all trial types was acceptable. The proactive and reactive markers were unreliable.

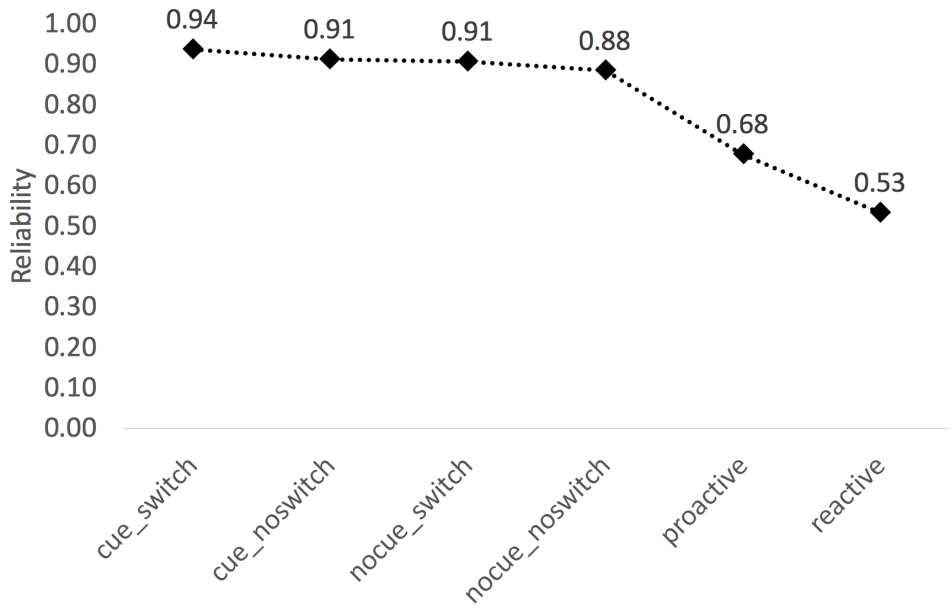


*Figure 11.* Reliability in Task-Switching Task.

### 3.1.4.2 Task-Switching Task Performance Results

In the task-switching task, RTs for correct trials are displayed in Figure 12. Participants' performance on no-switch trials was much better than that in switch trials in the cued condition, $t(97) = 10.263$, $p < .001$, $d = 1.037$. The same pattern was found in the non-cued condition, $t(97) = 14.879$, $p < .001$, $d = 1.503$. This means that the switch cost in both the cued and non-cued conditions are large and significant. See Figure 12. The correlation between the proactive and reactive markers was $r(98) = .392$, $p < .001$.

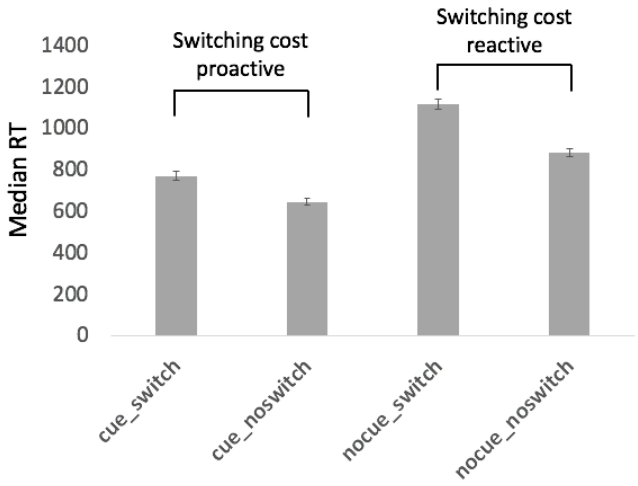


*Figure 12.* Performance in the Task-Switching Task.

## 3.2 Results of the Factor Analysis

After transforming the raw markers to *t*-scores (T=10*Z+50) for each task (using raw scores did not change the results), a series of factor analyses was conducted in SPSS using 'factor analysis' under the dimension reduction umbrella. The correlation matrix is shown in Table 2. The correlation between the proactive marker and the reactive marker was not significant in the AX-CPT, $r(98) = -.142$, $p > .05$. In the Stroop task, the proactive and reactive markers were weakly, but significantly and negatively correlated, $r(98) = -.218$, $p = .031$. In the Sternberg Working Memory task, the proactive and reactive markers were weakly, but positively, significantly related, $r(98) = .222$, $p = .028$. Finally, in the Task-Switching task, the proactive and reactive markers were moderately, positively correlated, $r(98) = .392$, $p < .001$. According to Gonthier et al. (2016), the proactive and reactive markers should not be correlated because they are independent.

Table 2

*Correlation Matrix for All Markers*

| | AX-CPT P | AX-CPT R | Stroop P | Stroop R | Sternberg P | Sternberg R | Task-Switching P | Task-Switching R |
|---|---|---|---|---|---|---|---|---|
| AX-CPT P | .364 | | | | | | | |
| AX-CPT R | -.142 | .561 | | | | | | |
| Stroop P | .001 | .080 | .496 | | | | | |
| Stroop R | .193 | -.156 | -.218* | -.106 | | | | |
| Sternberg P | -.161 | -.009 | -.111 | -.056 | .149 | | | |
| Sternberg R | .065 | .177 | .064 | .003 | .222* | .367 | | |
| Task-Switching P | -.070 | .113 | .185 | .027 | .032 | .015 | .679 | |
| Task-Switching R | .136 | .081 | -.081 | .080 | .218* | .033 | .392** | .534 |

Notes: Correlations on the diagonal are the split-half reliabilities with Spearman-Brown Correction.

*: Correlation is significant at the 0.05 level (2-tailed). **: Correlation is significant at the 0.01 level (2-tailed).

P = proactive marker; R = reactive marker.

### 3.2.1 Fixed Two-Component Factor Analysis

By setting the 'fixed number of factors' as two in SPSS, I conducted a fixed two-component factor analysis for the eight markers using principle components as extraction methods. The results did not load well on two factors. This means that the components of these markers from the four tasks that were reported to reflect the DMC are not consistent with two independent control mechanisms as hypothesized. See Table 3.

Table 2

*Fixed Two-Component Factor Analysis*

| | Component | |
|---|---|---|
| | 1 | 2 |
| AX-CPT Proactive | -.224 | .501 |
| AX-CPT Reactive | .491 | -.338 |
| Stroop Proactive | .457 | .157 |
| Stroop Reactive | .389 | .004 |
| Sternberg Proactive | .244 | -.465 |
| Sternberg Reactive | -.234 | .678 |
| Task-Switching Proactive | .655 | .202 |
| Task-Switching Reactive | .605 | .570 |

### 3.2.2 Fixed One-Component Factor Analysis

Next, by setting the 'fixed number of factors' as one in SPSS, I conducted a fixed one-component factor analysis to verify whether these markers could load well on one component. However, they failed to load well on one specific

component. This means that the components of these markers from the four tasks do not appear to reflect a single construct. See Table 4.

Table 3

*Fixed One-Component Factor Analysis*

| | Component |
|---|---|
| | 1 |
| AX-CPT Proactive | -.224 |
| AX-CPT Reactive | .491 |
| Stroop Proactive | .457 |
| Stroop Reactive | .389 |
| Sternberg Proactive | .244 |
| Sternberg Reactive | -.234 |
| Task-Switching Proactive | .655 |
| Task-Switching Reactive | .605 |

### 3.2.3 Exploratory Factor Analysis

Given that neither the fixed one- nor two-component factor analysis worked well for these eight markers, I conducted an exploratory factor analysis, by extracting components of which the eigenvalues are greater than 1 in SPSS. The scree plot below shows that there is no obvious pattern of number of components among these markers. See Figure 13.

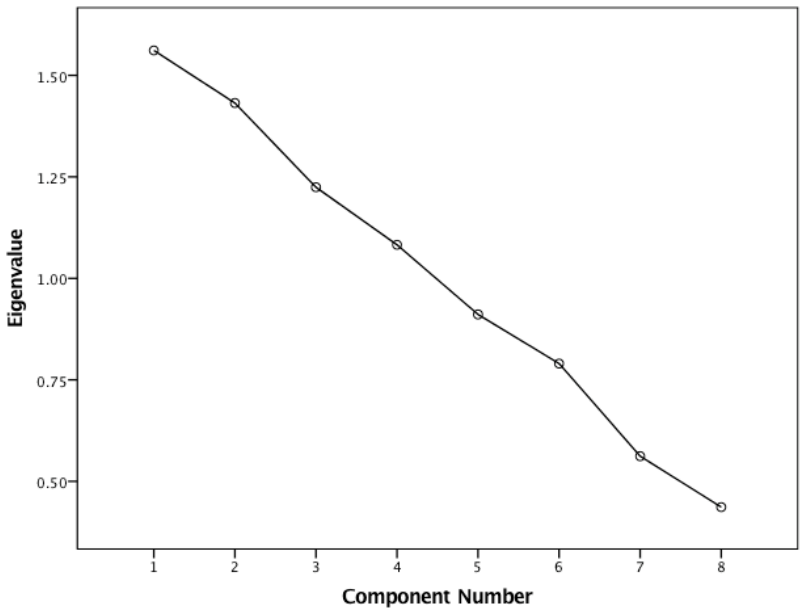


*Figure 13.* Scree Plot for Exploratory Factor Analysis.

# 4 Discussion

The objective of this study was to test the evidence for the independence of proactive control and reactive control according to the DMC framework, by conducting factor analysis. Four tasks that were proposed to test the DMC were used in this study. For each task, there was one marker for proactive control and one marker for reactive control.

According to Gonthier et al. (2016), the proactive and reactive markers should be independent. In the AX-CPT, the correlation between the proactive marker and reactive marker was not significant. In the Stroop task, the correlation between the proactive marker and reactive marker was negative and weak. In

the Sternberg Working Memory task, the correlation between proactive marker and reactive marker was positive and weak. Finally, in the task-switching task, the correlation between the proactive marker and reactive marker were moderately, positively correlated. These discrepant results do not clearly fit a theory suggesting independence nor a theory suggesting a clear inverse relationship.

Likewise, no pattern of components was found across tasks when conducting the factor analyses. This indicates that the markers supposedly measuring proactive control and reactive control appeared to each be measuring different constructs across the tasks.

Why might I have found these results? First, the reliabilities for each marker were low, suggesting that the markers from these tasks do not appear to be reliable measures of proactive and reactive control. The marker reliabilities were low despite the split-half reliabilities for trials in each task (e.g., RT in BY trials in AX-CPT; RT in cued switching trials in task-switching task) generally demonstrating high reliability.

Second, there were limitations for some tasks in this study. While the AX-CPT has been used to most to investigate the DMC, I did not manipulate conditions

that should elicit proactive or reactive control as I did with the other tasks. Rather, I used the task as it is most often used, which is primarily designed to elicit proactive control, but measure both proactive and reactive control.

I modified the Stroop task from the original Gonthier et al. (2016) task in three ways. 1) Participants in the present study responded via key press rather than verbally. Though the Stroop effects were significant in all conditions in this study, according to the finding from White (1969), nonverbal responses reduce interference compared to verbal responses. Thus, we might have found larger effects had our stimulus-response modality been compatible. It is also possible that this change in response modality changed the cognitive process being tapped. 2) I removed the 50% congruency trials because the primary evidence for the DMC is the high and low proportion congruency effect scores and to reduce possible fatigue effects because participants were completing multiple tasks. 3) The present task used 4 picture stimuli and 4 word stimuli rather than 8, as the original study used 4 additional pictures and corresponding words for the 50% congruency trials. There is no clear reason why the second and third changes would reduce the strength of the proactive and reactive control measures. In fact, removing the 50% congruency trials and only examining extreme proportion trials should have produced clearer effects. However, it is possible that one or more of these changes effected the results.

The task-switching task I used in this study was a modified version of the one originally used as a measure of the DMC, which used motivational incentives to induce proactive control. My variant of the task-switching task induced proactive control by using a location cue to allow participants to prepare for the forthcoming stimulus. I removed the cue to induce reactive control, as that is the only type of cognitive control possible in this condition. Thus, this measure should have produced clear, independent markers of proactive and reactive control. However, this is not what I found.

Although some of the tasks have potential limitations, no combination of markers, i.e., when removing any combination of tasks, loaded well on two fixed components or on one fixed component. Thus, no task limitation appears to be responsible for the lack of model fit.

A primary goal for future studies should be to establish more reliable behavioral markers for proactive and reactive control. The process to induce proactive and reactive control should be robust and verified across tasks.

# 5 Conclusion

Markers of proactive and reactive control were not found to be reliable within or across tasks. Factor analysis on eight markers did not load on either two fixed components corresponding to proactive control and reactive control or on one fixed component. Exploratory factor analysis did not reveal an obvious pattern for these markers. I did not find evidence to support the DMC theory in this study.

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