Cognitive control and binding in context-based decision-making : normal and dopamine deviant populations

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Chapter 2

Proactive Control and Episodic Binding in Context Processing Effects

Abstract

Decision-making often involves using prior contextual information to evaluate relevant events. A laboratory equivalent of context processing situations, the *AX*-Continuous Performance Task (*AX*-CPT), yields errors when a target probe appears in a nontarget context, or when a nontarget probe appears in a target context. According to goal-driven accounts, context information is used for top-down preparation towards processing context-appropriate information. Performance costs on nontarget trials are attributed to inefficient cognitive control. In contrast, the episodic-binding account predicts that prior experiences with combinations of a context, probe, and response are bound in episodic memory and thus bias future actions. Performance costs in this view are caused by the need to overrule prepotent associations. The current experiments tested the relative importance of proactive cognitive control versus episodic learning of appropriate stimulus-response relations for CPT performance. Support was obtained for both contributions.

Introduction

Maintaining the contents of working memory (WM) and adjusting it to the task at hand involves cognitive control. By cognitive control we refer to the properties of the cognitive system that emerge as we configure basic cognitive processes in accordance with instructions, intentions and (rapidly changing) environmental demands. For example, a car driver approaching a crossroad has to organize task goals (getting to a specific destination before a specific time), task representations (traffic rules; car operating principles), task context (recent and current road signs; road map information constraining the possible routes from A to B), and incoming sensory information (current traffic and position relative to destination). Performing such a complex task involves top-down proactive control (anticipating and preparing for certain situations and events) as well as reactive control (flexible adaptive responding to unanticipated situations and events). In addition, such tasks involve the formation of episodic associations between temporally adjacent relevant events. The stronger the association between specific events, the more reliably they can be used for routine-like control over behavior, but also the more difficult it will be to overcome these associations when the current situation calls for different behavior. In the current study, the importance of episodic binding vis-à-vis proactive control processes in activating the task context will be tested in a continuous performance task (CPT).

Proactive cognitive control and context processing

The importance of proactive control processes in the maintenance and updating of WM content is largely beyond controversy (e.g., Miller & Cohen, 2001). Failures to update the current task goal are reflected in perseverative behavior under conditions that actually require a switch from one set of task rules to another, as in set shifting experiments (Jersild, 1927) or in the Wisconsin Card Sorting Task (Grant & Berg, 1948; Milner, 1963). Failures to implement and maintain a goal-driven decision bias may lead to distractibility, for example in the Stroop color-word task (Stroop, 1935) or the Eriksen flanker task (Eriksen & Eriksen, 1974) if task-irrelevant information captures attention and elicits an inappropriate response.

Failures to maintain or update WM content are also illustrated by performance errors on the *AX*-CPT (e.g., Braver & Barch, 2002), a variant of the classic CPT task (Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956) and focus of the current study. Braver and colleagues (Braver & Barch, 2002; Braver, Satpute, Rush, Racine, & Barch, 2005) used the term *context representation* to refer to representations that influence planning, behavior and attentional processes. The context can contain task instructions, information from prior stimuli, or intended actions. It configures the cognitive system for the performance of challenging and nonroutine tasks.

According to the context processing model (Braver & Barch, 2002; Braver, Barch, & Cohen, 1999; Braver et al., 2001), context information is part of the representations in WM. For each new incoming contextual stimulus (referred to here as context cues) the model changes its current context representation, which helps in interpreting imperative stimuli (referred to here as probes). Top-down control can be exerted because the context cue (as currently represented in prefrontal cortex, PFC) biases or primes the activation of a response or goal, as previously associated with that particular cue, in succeeding trials. On the other hand, pre-existing associations between specific probe stimuli and specific responses can create a bottom-up bias in responding. Some probe stimuli are for example more strongly associated to one action, while others have become associated more strongly to another action. When context updating or maintenance is not intact, response activation may be driven more strongly by these probe-response associations than by context cues. The hypotheses generated by the context processing model have been tested using the *AX*-version of the CPT (*AX*-CPT, Braver & Barch, 2002; Braver et al., 1999, 2001).

AX-CPT paradigm

The *AX*-CPT paradigm is a modified version of the classic CPT (Rosvold et al., 1956). During each *AX*-CPT trial, participants are presented with a sequence of stimuli containing a context cue (*A* or *B*) and a probe (*X* or *Y*) on the computer screen. They have to respond to a target probe (*X*) with a manual response on the keyboard, the target response key, but only when the target probe was immediately preceded by a specific context cue (*A*). In every other case, for example in *AY, BX* or *BY* sequences, they have to respond to a probe with a nontarget response key. *AX* trials occur very frequently during the experiment to induce a strong tendency to make a target response to the *X* probe.

Goal-driven bias and CPT

Performance errors on the *AX*-CPT have been interpreted commonly in terms of impulsivity, attention, or inhibition (Halperin, McKay, Matier, & Sharma, 1994; Riccio, Waldrop, Reynolds, & Lowe, 2001). Target trials (*AX*) typically occur on the majority of trials in the *AX*-CPT task, and this probability induces a strong bias to issue a target response, even on trials other than *AX* (*BX* and *AY*).

According to the context processing model, context information must therefore be used in these trials to give the appropriate nontarget response and overcome the bias to activate the target response. Braver et al. (Braver & Barch, 2002; Braver et al., 1999, 2001) hypothesized that in intact context processing (i.e., representation, updating and maintenance of context) *AX*-CPT performance is better (faster and more accurate) on *AX* than on *AY* and *BX* trials. On *AY* trials, subjects incorrectly expect a target probe to appear after an *A* context cue and are thus inclined to respond with an incorrect (target) response (false alarm). If performance would be entirely goal-driven or rule based, performance would be hampered exclusively on *AY* trials, because in *BX* trials intact context maintenance would result in correct rejection. However, performance in *BX* trials is often hampered by the *X* probe which is strongly associated with an *A* context and target response. Thus, performance costs in *BX* trials may be due to inefficient proactive preparation or the result of strong stimulus-response associations, or both. The present study sought to evaluate the contribution of goal-driven control and episodic item-specific bindings in an *AX*-CPT task.

Stimulus-driven accounts

Instead of via proactive preparation, a decision can be biased by currently available stimulus information that reactivates previously associated information from episodic memory. The associative account has recently received some support; performance costs attributed to top-down control may be confounded with episodic effects (e.g., Mayr, Awh, & Laurey, 2003; Nieuwenhuis et al., 2006), thus it seems relevant to consider whether they may play a role in the *AX*-CPT task as well.

The feature integration account advocated by Hommel (2004; Hommel, Proctor & Vu, 2004) emphasizes a bottom-up (stimulus-driven) influence and the effect of stimulus-stimulus or stimulus-response associations on current performance, rather than a proactive control bias. The binding account proposes that on every occurrence of a perceived event, task-relevant or salient information (i.e. certain stimulus and response features) is temporarily bound into an episodic memory trace, a so-called event file (Hommel, 2004). If a feature of the encoded event is encountered on a subsequent occasion, this feature reactivates the associated features from the previously created event file. Performance can be hampered on succeeding trials if only one feature of an event file is reactivated and the other not. This is the case, for instance, when a stimulus feature is repeated, but the associated response (as encoded in the event file) is incompatible with the currently correct response. The elements of the event file then have to be unbound or rebound which takes time and is error-prone. As a result, performance is worse compared to a situation in which stimulus and action features are both repeated or both changed (Hommel, 1998, 2004).

Recently, both goal-driven accounts and stimulus-driven accounts have been shown to explain behavioral performance costs in several experimental paradigms (for a review see Egner, 2007; Verguts & Notebaert, 2008). Studies on negative priming (Huang, Holcombe, & Pashler, 2004; Tipper, 2001), inhibition (Verbruggen, Logan, Liefooghe, & Vandierendonck, 2008), task switching (Waszak, Hommel, & Allport, 2004), and spatial incompatibility (Hommel et al., 2004) indicated that the reactivation of competing information as a result of a retrieved episodic binding created on a previous trial, bias performance on the current trial.

Stimulus-specific episodic bindings in the *AX*-CPT may arise between context cue stimuli, probe stimuli, and responses, and can affect performance on subsequent trials in the task. Thus, the binding account may give rise to a different explanation for the costs associated with *AY* and *BX* pairs in the *AX*-CPT than an entirely proactive goal-based account would. The features *A*, *X*, and target response become strongly associated with each other because of their prevalent occurrence. When an *AY* pair is presented incidentally, the *A* context cue activates the representations of the *X* probe stimulus and the target response; unbinding and re-binding is then either slow or unsuccessful. Likewise, when a *BX* pair is presented incidentally, the *X* probe will activate the associated representations of the *A* cue and the target response; again, unbinding and re-binding may either fail or consume time.

Overview of the current study

The aim of the present study is to establish whether, in addition to proactive goal-driven biases, stimulus-specific mechanisms can explain part of the variance in performance on the *AX*-CPT. One possibility is that a goal-driven bias will influence *AY* and *BX* performance without any effect of bindings between cue, probe, and response on performance. Alternatively, the effect of event binding might fully explain the variance in *AY* and *BX* performance. A third scenario might be that goal information as well as the influence of episodic bindings each partially account for the *AY* and *BX* effects.

To investigate these differential accounts, the traditional use of characters (*A, B, X* and *Y*) was replaced by words (cues *A, B*) and pictures of faces (probes *X, Y*). Word and face stimuli should allow participants to distinguish between occurrences of specific context cues and probes on individual trials and to create separate event files for separate combinations of features. Previous research by Colzato, Raffone, and Hommel (2006) showed that the bindings between stimulus features are most powerful when using real-life pictures as compared to arbitrary feature conjunctions.

Subjects were asked to respond with a specific response based on the features of cues (words; presented uppercase or lowercase) and probes (pictures of faces; male or female). For example, an uppercase word succeeded by a female face asked for a target response.

Table 1

Main contrasts of interest (with examples) to compare binding and goal-driven accounts. Examples of AX trials (word uppercase, female face) in this table consist of fixed word picture pairs.

Theory	**Example**			**Test**
	Cue	**Probe**	**Trialtype**	
Goal-driven	Uppercase word: HORSE	Female face 1	(AX)	*AX >AY*
	Uppercase word: HORSE	Male face 1	(AY)	
Binding	Uppercase word: HORSE	Female face 1	(AX)	*AX =BX*
	Lowercase word: fire	Female face 1	(BX)	
	Uppercase word: HORSE	Male face 1	(A_xY)	$A_yY > A_xY$
	Uppercase word: COFFEE	Male face 1	(A_yY)	
	Lowercase word: fire	Female face 1	(BX_a)	$BX_b > BX_a$
	Lowercase word: fire	Female face 2	(BX_b)	
Goal-driven & binding	Uppercase word: HORSE	Female face 1	(AX)	$AX > A_yY > A_xY$
	Uppercase word: HORSE	Male face 1	(A_xY)	
	Uppercase word: COFFEE	Male face 1	(A_yY)	
	Uppercase word: HORSE	Female face 1	(AX)	$AX = BX_b > BX_a$
	Lowercase word: fire	Female face 1	(BX_a)	
	Lowercase word: fire	Female face 2	(BX_b)	

Hypotheses

A purely proactive goal-driven bias would predict that performance on the *AX*-CPT task relies on the correct representation and maintenance of rule information, predicting more errors on *AY* trials than on *AX* trials. Note that the context processing model does take into account that associations between probe and target response drive performance which might lead to additional errors on *BX* trials. However, with intact context processing, they are thought to occur less often than *AY* errors.

In terms of the current stimuli, a participant may be instructed to give a target response to the picture of a female face preceded by a word in UPPERCASE script (*AX* trial). Because uppercase words are frequently followed by female faces, the word induces bias for a target response, also if it is followed by a male face (*AY* trial). Because female faces often require a target response, these faces induce a bias for a target response even if it is preceded by a lowercase word (*BX* trial).

A stimulus-specific binding account predicts that every occurrence of a context cue and a concurring target feature is bound into an event file. When on subsequent trials one of these features must be bound to a competing feature code it takes time to build a new association. The costs of processing a probe that deviates from a dominant association are investigated by comparing two types of *AY* and two types of *BX* trials that differ in association strength between context cues and probes. That is, some stimuli are presented in consistent combinations, thereby leading to strong binding and associated bias, and others in random combinations, thus leading to no bias. Table 1 shows trial examples for the main contrasts of interest.

When a specific target probe is shown consistently in the context of a particular word [an AX trial, *FIRE* - *female face 1*], then these specific context cue and probe are represented as a unitary episodic-memory trace. If on a later occasion this particular context cue is succeeded by a photo of a context-inappropriate *Y*-probe, [*FIRE* - *male face*], then this context cue has to be unbound from the association with the female face and target response. This is time-consuming and prone to failure, explaining the *AY* costs. Other context cues, however, from regular *AY* cue-probe pairs [*TABLE* - *male face*], are never succeeded by a context-appropriate target probe [*female face*] throughout the experiment, thus no unbinding of the context cue from a previously associated probe is necessary and performance on these trials should not be time-consuming or error-prone.

Thus, a stimulus-specific binding account predicts that *AY* costs occur only for *A*-context cues that are associated *consistently* with a particular *X*-probe [A_xY trials], but not for those context cues that are paired *nonsystematically* to varying context-inappropriate *Y*-probes [A_yY trials]. Recall that if decisions entirely depend on proactive goal-driven preparation, these types of context cues are indistinguishable and *AY* costs are equivalent in both cases.

BX costs can be explained similarly; the binding account predicts that *BX* costs occur only for *X*-probes that are associated consistently with particular *A*-context cues [BX_a trials], but not for those probes that are paired inconsistently to varying *B*-context cues [BX_b trials]. Consider again an *AX* pair [*WATER* - *female face 2*]. If on a later occasion *female face 2* is presented in an inappropriate *B*-context *train*, then this probe has to be unbound from the association with the context *WATER* which is time-consuming and error-prone. Other probe pictures are never preceded by *A*-context cues, but always by varying *B*-context cues, for example [*house* - *female face 3*]. Throughout the experiment *female face 3* was never presented in an *A*-context *WATER*, thus the *X*-probe was never bound together with an *A*-context cue or target response. Hence, no time-consuming or error-prone unbinding costs are predicted on these BX_b trials. Again, if performance is merely goal-driven *B*-cue information will override any type of *X*-probe and thus performance will be equivalent across all types of *BX* pairs.

The current study consists of two experiments. Experiment 1 investigated the contribution the goal-driven and stimulus-driven bias in an adapted *AX*-CPT. To test whether binding effects would be subject to decay, the cue-probe interstimulus interval was varied between subjects. Experiment 2 was employed to replicate and extend the results of experiment 1 with a more difficult version of the *AX*-CPT, which was accomplished by introducing a distracter between cue and probe.

EXPERIMENT 1

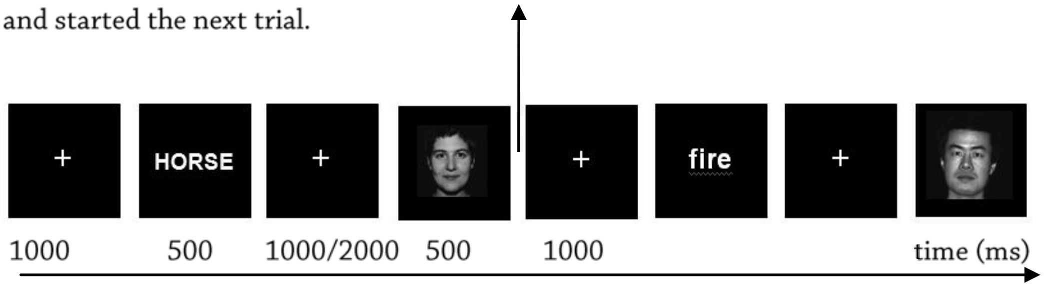
Method

Participants

Twenty-two young adults (students from Leiden University, average age 21.4 years, 17 females) participated in this experiment. The experiment lasted one hour. The experiment was conducted in accordance with relevant laws and institutional guidelines and was approved by the local ethics committee from the Faculty of Social Sciences. Before starting the experiment each participant read and signed an informed consent. Participants either received course credits or €7 remuneration for their participation.

Figure 1

Trial structure of the adapted AX-Continuous Performance Task. Example of an AX and BY trialtype are depicted. Subjects were instructed to respond with presentation of the probe-picture. In the current example they pressed a target response button if a female picture followed an uppercase word (AX) and in any other case pressed a nontarget response button (AY, BX, BY).



With responses slower than 500 ms a fixation point remained on the screen for an additional 1000 ms. Subjects' response terminated the current trial and started the next trial.

Procedure

The experiment started with an instruction that explained the task rule and two practice blocks. Subjects viewed sequences containing pairs of cues (words) and probes (photos) on the computer screen. They had to respond to a female face (probe) with a manual response on the M-key, but only when the preceding word was in uppercase. To a male face, or to a female face following a word in lowercase, they had to respond with a Z-key. The assignment of response keys, word case, and the gender-target relation was counterbalanced across subjects. Long (2000 ms) and short (1000 ms) cue-probe intervals were varied between subjects.

Participants responded to the probe stimuli with either a target or nontarget response, but not to context cues (as in the classic *AX*-CPT). Each trial started with a fixation point (1000 ms), followed by a context word (500 ms). Then a blank screen appeared after either 1000 or 2000 ms (between subjects factor). Finally the imperative stimulus appeared (a picture of a face, 500 ms). After that, a blank screen appeared until a response was given (i.e., maximally 1000 ms, thus subjects had to respond within 1500 ms). Feedback was presented by means of a “beep” sound if participants responded incorrectly or too slow. Figure 1 presents an example trial.

The experiment consisted of seven blocks of 120 trials; each block took approximately 10 minutes to complete. Practice before the experiment consisted of two practice blocks. First participants practiced on a block of 21 trials with equal probabilities of each experimental condition; subsequently they practiced on a block of 44 trials resembling an experimental block, also in terms of trial-type frequency. Trialtypes occurred with a predetermined frequency, which is explained in the design, and were randomly presented within each block.

Stimuli and Apparatus

This experiment used a word-picture based version of the *AX*-CPT task to measure RT and percentage of errors in each condition (which is determined by the cue-probe combinations). The context cues that represent analogues of the *A* and *B* letter stimuli from the classic *AX*-CPT consisted of words (cues). The analogues of the probe letters *X* and *Y* were grayscale front-view photographs of faces of men (10) and women (10) (probes). Words (15) were selected from the Celex database (Burnage, 1990). They contained three to six characters and were conceptually as unambiguous as possible. The average frequency of occurrence of the words chosen was 128 times per million words.

Stimuli were presented by E-prime software on 17 inch CRT monitors; participants viewed the computer screen from a distance of approximately 75 cm and with a visual angle of 7.64°.

Design

The experimental design consisted of different *A*-cue types (in A_xY and A_yY trials) and different *X*-probe types (in BX_a and BX_b trials), to test the predictions from the binding account. The subscript indicates the bias induced for the association between a specific picture and a context word.

The frequencies and stimulus identities for each trial pair are reviewed below. Examples and contrasts of interest are displayed in Table 1. *A*-cues were represented by ten unique words (five A_x- and five A_y-cues) and *B*-cues by five unique words. Uppercase or lowercase presentation determined whether a word was an *A*- or *B*-cue. Likewise, *X*-probes consisted of ten distinctive face pictures (five for X_a and five for X_b trials) and *Y*-probes of five distinctive face pictures (the gender that was not used for *X*-probes). Gender of the faces determined whether a probe was an *X*-target probe or a *Y*-nontarget probe.

AX pairs, presented on 65% of all trials

A valid context cue followed by a target probe, for example an uppercase word followed by a female face. *AX* trials were presented at a relatively high frequency during the experiment (65%) to induce a bias to respond towards *A*-cues and *X*-probes. *AX* trials consisted of five unique (fixed) pairs of cue and probe.

BY pairs, presented on 10% of all trials

BY trials were random combinations of *B*-cue words (5) and *Y*-probe pictures (5).

BX_a pairs, presented on 5% of all trials

The specific X-probe in a $\underline{BX_a}$ pair is one of the X-probes that in 65% of all trials is preceded by an A-cue, but is preceded here by a B-cue (different word presented in lowercase). BX_a pairs consisted of random combinations of B-cue words (5) and X_a-probe pictures (5).

BX_b pairs, presented on 5% of all trials

The specific X-probe in a $\underline{BX_b}$ pair is not among the X-probes that in 65% of all trials is preceded by an A-cue, but is always preceded by a randomly selected B-cue. BX_b pairs consisted of random combinations of B-cue words (5) and X_b-probe pictures (5).

A_xY pairs, presented on 5% of all trials

The specific A-cue in an A_xY pair is one of the A-cues that in 65% of all trials is followed by an X-probe, but is followed here by a Y-probe. A_xY pairs consisted of random combinations of A_x-cue words (5) and Y probe pictures (5).

A_yY pairs, presented on 5% of all trials

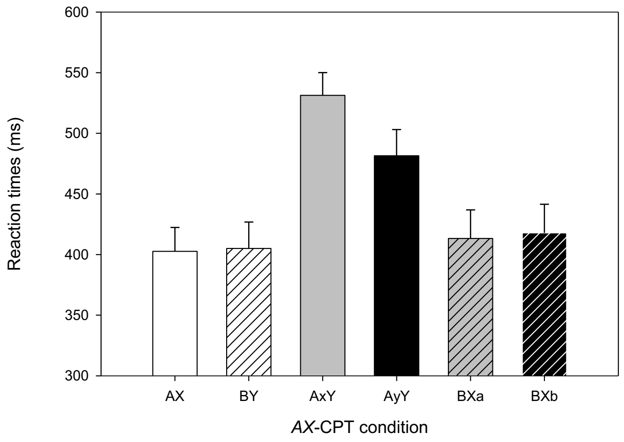
The specific A-cue in an A_yY pair is not among the A-cues that in 65% of all trials is followed by an X-probe, but is always followed by a randomly selected Y probe. A_yY pairs consisted of random combinations of A_y-cue words (5) and Y-probe pictures (5).

B-NoGo pairs, presented on 5% of all trials

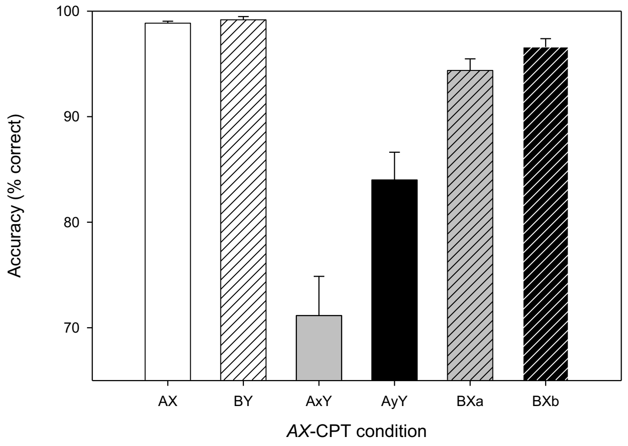
B-NoGo trials were random combinations of B-cue words (5) and a probe picture of a stop signal. A stop signal consisted of a red octagon with the word “stop” printed on it. Incidental No-go probes, which required participants to refrain from responding, were included to ascertain that attention would be sustained following the B cue.

Figure 2

a. Mean reaction time (ms) by AX-CPT condition, Experiment 1. Error bars represent standard errors.



b. Mean percentage correct (%) by AX-CPT condition, Experiment 1. Error bars represent standard errors.



Statistical Analysis

Trials with reaction times shorter than 150 ms or longer than 2000 ms were removed from the analyses. Performance on each trial type (*AX, AY, BX, BY*) was measured by mean accuracy (percentage correct) and mean reaction time (for correct responses).

Reaction times and accuracy were analyzed separately with repeated-measures analysis of variance (ANOVA). Simple contrasts and simple pair-wise comparisons were used to test specific hypotheses. The significance level for all analyses was set to 0.05. Whenever the assumption of sphericity was violated, degrees of freedom were adjusted according to the Greenhouse-Geisser correction method.

Results and discussion

The results section is organized according to the theoretically relevant hypotheses, displayed in Table 1. Mean RT and accuracy are displayed in Figures 2A and 2B.

The first analysis tested whether binding effects would be subject to decay by comparing A_xY-A_yY and BX_a-BX_b in long and short interstimulus intervals (ISI). The second analysis tests binding and goal-driven context effects in A_xY-A_yY, BX_a-BX_b and *AX-AY-BX* trials, respectively. Finally, *BY* trials were contrasted with *AY* and *BX* trials to test goal-driven context effects.

ISI binding analysis

An ANOVA on RT with the within-subjects factor Trial Type (*AY, BX*), Binding (Associated, Unassociated) and between-subjects factor ISI (short, long) revealed no significant effect of ISI, F (1, 20) = 0.54, MSE = 137183, p = 0.47, nor any interaction effect involving ISI, Fs < 0.32, ps > 0.58. The analogous ANOVA on accuracy, however, yielded a significant effect of ISI, F (1, 20) = 12.7, MSE = 140, $p < 0.05$. Performance was more accurate with a short compared to a long ISI, especially in *AY* trials, $F_{AYBX*ISI}$ (1, 20) = 4.5, MSE = 192.86, $p < 0.05$. Subjects' performance on *AY* trials compared to *BX* trials was more accurate with a short ISI ($M_{AYshort}$ = 85%, $M_{BXshort}$ = 97%) than with a long ISI

(M_{AYlong} = 70%, M_{BXlong} = 94%). No interactions of ISI with binding were found, *Fs* < 2.0, *ps* > 0.17.

Because ISI did not affect binding effects, between-subjects data were collapsed and ISI was not included as a factor in subsequent analyses.

AX-AY-BX analyses

Reaction times

An ANOVA with the within-subjects factor Trial Type (*AX, AY, BX*) revealed a significant effect of Trial Type, *F* (2, 42) = 75.82, *MSE* = 947.05, $p < 0.001$. Simple contrasts indicated that performance on *AX* (M_{AX} = 403 ms) trials was significantly faster than the mean of the *AY* conditions (M_{AY} = 508 ms), *F* (1, 21) =133.72, *MSE* =1816.86, $p < 0.001$, and nearly significantly faster compared to the mean of *BX* conditions (M_{BX} = 417), *F* (1, 20) = 3.5, *MSE* = 1193.46, *p* = 0.08. Pair-wise comparisons revealed that *AX* was significantly faster than A_yY trials (M_{AyY} = 483 ms), *t* (21) = -8.12, $p < 0.001$. Also, performance on A_yY trials was significantly faster than on A_xY trials (M_{AxY} = 533 ms), *t* (21) = -4.17, $p < 0.01$. However, pair-wise comparisons showed only a trend towards a significant difference between *AX* and BX_b trials (M_{BXb} = 419 ms), *t* (21) = -1.86, *p* = 0.08. Additionally, performance on BX_a (M_{BXa} = 414 ms) was not significantly different from performance on BX_b trials, *t* (21) = 0.74, *p* = 0.47.

Accuracy

The analogous ANOVA on accuracy also showed a significant effect of Trial Type, *F* (2, 42) = 42.89, *MSE* = 127.44, $p < 0.001$. Moreover, simple contrasts showed that *AX* trials (M_{AX} = 99%) differed significantly from the mean of the *AY* conditions (M_{AY} = 77 %), *F* (1, 21) = 57.29, *MSE* = 184.72, $p < 0.001$, and of the *BX* conditions (M_{BX} = 95 %), *F* (1, 21) = 14.36, *MSE* = 18.28, $p < 0.01$. Pair-wise comparisons showed that performance on *AX* trials was more accurate than on A_yY trials (M_{AyY} = 84%), *t* (21) = 5.70, $p < 0.001$, and performance on the latter was significantly more accurate than on A_xY trials (M_{AxY} = 70 %), *t* (21) = 3.58, $p < 0.01$. Additionally, subjects performed more accurately on *AX* than on BX_b trials (M_{BXb} = 97%), *t* (21) = 2.78, $p < 0.05$, and more accurately on BX_b than on BX_a trials (M_{BXa} = 94%), *t* (21) = 2.47, $p < 0.05$

BY-AY-BX analysis

Reaction times

An ANOVA of RT with the within-subjects factor Trial Type (*BY*, *AY*, *BX*) revealed a significant effect of Trial Type, $F\ (2, 42) = 79.20$, $MSE = 1460.92$, $p < 0.001$. Contrast analysis indicated that performance on *BY* trials ($M_{BY} = 405$ ms) was significantly faster than the mean of the *AY* conditions, $F\ (1, 21) = 102.58$, $MSE = 2254.33$, $p < 0.001$, and the mean of *BX* conditions, $F\ (1, 21) = 7.83$, $MSE = 348.36$, $p < 0.05$. Pair-wise comparisons showed that *BY* performance was significantly faster than A_yY trials, $t\ (21) = -6.04$, $p < 0.001$, and BX_b trials, $t\ (21) = -2.83$, $p < 0.05$.

Accuracy

The analysis of accuracy also showed a significant effect of Trial Type, $F\ (2, 42) = 43.89$, $MSE = 126.73$, $p < 0.001$. Moreover, the contrast analysis showed that *BY* ($M_{BY} = 99\%$) performance was significantly more accurate than the mean of the *AY* conditions ($M_{AY} = 78\%$), $F\ (1, 21) = 59.61$, $MSE = 182.71$, $p < 0.001$, and the mean of *BX* conditions ($M_{BX} = 95\%$), $F\ (1, 21) = 16.72$, $MSE = 18.73$, $p < 0.01$. Pair-wise comparisons revealed that *BY* performance was significantly more accurate than on A_yY trials, $t\ (21) = 5.95$, $p < 0.001$, and BX_b trials, $t\ (21) = 3.24$, $p < 0.05$.

In sum, in line with the binding account, stimulus-specific costs were increased in A_xY versus A_yY, and in BX_a compared to BX_b trials. That is, the performance costs associated with *AY* trials were more pronounced on trials in which the cue was previously associated with a specific *X*-probe (A_xY), compared to A_yY trials that lacked any previous association of the cue with a particular *X*-probe. Likewise, performance costs associated with *BX* trials were more pronounced on trials in which the probe was previously associated with a specific *A*-cue (BX_a), compared to BX_b trials that lacked any previous association of the probe with a particular *A*-cue.

However, performance costs were still present in A_yY and BX_b trials compared to *AX* and *BY* trials. This pattern supports theories of top-down control only in part, because an entirely goal-driven approach did not predict costs on BX_b trials. Thus, predictions from the episodic binding account as well as from top-down control accounts were confirmed: a goal-driven bias was present in A_yY trials (not predicted by the binding account) whereas these performance costs increased with mismatching cue-probe bindings (A_xY, BX_a) (not predicted by the goal-driven account). Performance costs on BX_b trials most likely result from a category-based association between *X*-probe and target response whereas the increase of these costs in BX_a trials are due to stimulus-specific associations.

Note that BX_a performance costs were not expressed in slowed RTs. Although most previous studies have not reported on RT effects in the *AX*-CPT task, the presence of *BX* costs on accuracy in the absence of *BX* costs on RT was somewhat unexpected. This absence may relate to lack of task difficulty: the *B*-cue was always fully predictive of the response choice, irrespective of the subsequent probe, which may have resulted in fast response times on both BX_a and BX_b trials. Therefore, Experiment 2 served to extend the findings of Experiment 1, but with a more difficult version of the task to replicate the current findings and exclude the possibility that the absence of RT costs in Experiment 1 resulted from floor effects.

EXPERIMENT 2

Method

Participants

Twenty-two young adults (students from Leiden University, average age 19.8 years, 20 females) participated in this experiment. None of these had participated in Experiment 1. The experiment lasted one hour and 15 minutes. Participants either received course credits or €8,- remuneration for their participation.

Procedure

The procedure remained identical to Experiment 1, with the exclusion of the between-subjects factor of inter-stimulus interval.

Stimuli, apparatus and design

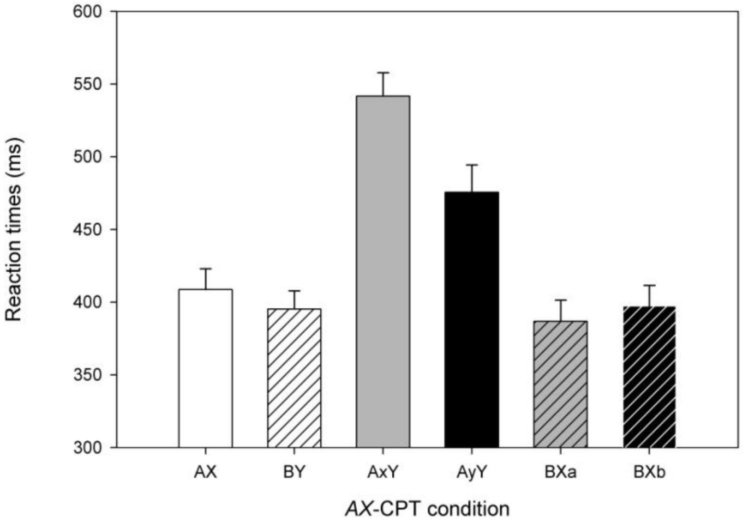
Experiment 2 used the same cue and probe stimuli and a similar design as Experiment 1. The inter-stimulus interval was now fixed to 2500 ms for all participants. Additionally, distracter stimuli were introduced in the inter-stimulus interval. Distracters were nonwords, consisting of 4 or 5 letters each, presented as a random selection of capital and small letters (within the nonwords). These nonwords were presented for a duration of 2500 ms, starting subsequent to the offset of the cue stimulus.

Statistical analysis

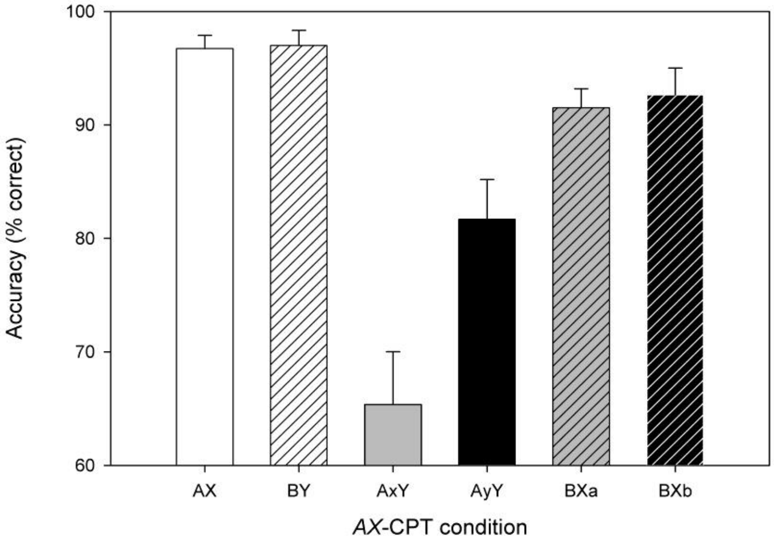
The statistical analyses performed were similar to Experiment 1, with exception of the ISI analysis.

Figure 3

a. Mean reaction time (ms) by AX-CPT condition, Experiment 2. Error bars represent standard errors.



b. Mean percentage correct (%) by AX-CPT condition, Experiment 2. Error bars represent standard errors.



Results and discussion

The results are organized according to the theoretically relevant hypotheses, displayed in Table 1. Mean RT and accuracy are displayed in Figures 3A and 3B.

AX-AY-BX analyses

Reaction times

An ANOVA on RT with the within-subjects factor Trial Type (*AX, AY, BX*) revealed a significant effect, F (2, 42) = 113.29, MSE = 770.69, $p < 0.001$. Simple contrasts revealed that performance on *AX* (M_{AX} = 409 ms) trials was significantly faster than the mean of the *AY* conditions (M_{AY} = 509 ms), F (1, 21) = 217.48, MSE = 1008.77, $p < 0.001$, and nearly significantly slower compared to the mean of the *BX* conditions (M_{BX} = 392 ms), F (1, 21) = 3.78, MSE =1603.32, p = 0.07. Pair-wise comparisons indicated that *AX* was significantly faster than A_yY trials (M_{AyY} = 476 ms), t (21) = -6.19, $p < 0.001$, but not compared to BX_b trials (M_{BXb} = 397 ms), t (21) = 1.29, p = 0.21. Furthermore, performance on A_yY trials was significantly faster than performance on A_xY trials (M_{AxY} = 542 ms), t (21) = 3.89, $p < 0.01$. However, performance on BX_a (M_{BXa} = 387 ms) was not significantly different from performance on BX_b trials, t (21) = 1.56, p = 0.14.

Accuracy

The analogous ANOVA on accuracy also showed a significant effect of Trial Type, F (2, 42) = 40.64, MSE = 114.85, $p < 0.001$. Moreover, simple contrasts showed more accurate performance on *AX* trials (M_{AX} = 97 %) than the mean of the *AY* conditions (M_{AY} = 74 %), F (1, 21) = 61.31, MSE = 193.21, $p < 0.001$, and than the mean of *BX* conditions (M_{BX} = 92 %), F (1, 21) = 7.74, MSE = 61.70, $p < 0.05$. Pair-wise comparisons revealed more accurate performance on *AX* than on A_yY trials (M_{AyY} = 82 %), t (21) = 4.96, $p < 0.001$. Additionally, accuracy on A_yY trials was significantly higher than on A_xY trials (M_{AxY} = 65%), t (21) = -3.38, $p < 0.01$. *AX* trials compared to BX_b trials (M_{BXb} = 93 %) were not significantly different, t (21) = 1.87, p = 0.07, nor BX_a versus BX_b, t (21) = -0.82, p = 0.43. Subjects did not perform more accurately on BX_b than BX_a trials (M_{BXa} = 92 %).

BY-AY-BX analysis

Reaction times

An ANOVA of RT with the within-subjects factor Trial Type (*BY, AY, BX)* revealed a significant effect, F (2, 42) = 143.71, MSE = 865.22, $p < 0.001$.

Simple contrasts indicated that BY (M_{BY} = 395 ms) performance was significantly faster than the mean of the *AY* conditions, F (1, 21) = 225.58, MSE = 1253.73, $p < 0.001$, but not compared to the mean of *BX* conditions, F (1, 21) = 0.27, MSE = 780.09, p = 0.61. Pair-wise comparisons showed that performance on *BY* trials was significantly faster than on A_yY trials, t (21) = -6.5, $p < 0.001$, but not compared to BX_b trials, t (21) = -0.36, p = 0.72.

Accuracy

The analysis of accuracy also showed a significant effect of Trial Type, F (2, 42) = 45.29, MSE = 128.25, $p < 0.001$. Moreover, simple contrasts showed that performance on *BY* trials (M_{BY} = 97%) was significantly more accurate than the mean of the *AY* conditions, F (1, 21) = 64.91, MSE = 186.82, $p < 0.001$, and than the mean of *BX* conditions F (1, 21) = 21.12, MSE = 25.34, $p < 0.001$. Pair-wise comparisons revealed more accurate performance on *BY* trials than on A_yY trials, t (21) = 5.27, $p < 0.001$, and than on BX_b trials t (21) = 3.05, $p < 0.01$.

In sum

As predicted by the binding account, stimulus-specific costs were increased in A_xY versus A_yY trials. But unlike predictions from the binding account, stimulus-specific costs were not enhanced in BX_a compared to BX_b trials. By and large, this pattern replicates the findings of Experiment 1. Additionally, Experiment 2 served to increase task difficulty, as indicated by a lower accuracy than in Experiment 1 ($\text{Mean}_{\text{exp1}}$ = 90 %, $\text{Mean}_{\text{exp2}}$ = 87 %, BX_{exp1} = 95%, BX_{exp2} = 92 %), even though RTs were not slower than in Experiment 1 ($\text{Mean}_{\text{exp1}}$ = 442 ms and $\text{Mean}_{\text{exp2}}$ = 432 ms).

Thus, it is unlikely that the absence of RT costs in Experiment 1 could be attributed to too low task difficulty (and hence floor effects). With the more difficult task version in Experiment 2, *BX* accuracy data now show similar results as the RT data (of both Experiments 1 and 2), that is, no difference between *BXa* and *BXb* trials.

Therefore, we suggest that the findings of Experiment 2 provide additional support for the notion that stimulus-specific bindings affect performance in *AY* but not *BX* trials. In the general discussion we speculate about a possible explanation for this finding.

Furthermore, performance costs were increased in A_yY trials compared to *AX* and *BY* trials as predicted by the goal-driven account. Additionally, costs were increased in BX_b trials compared to *BY* trials, due perhaps to a category-based association between *X*-probe and target response.

General discussion

The current study identified whether stimulus-specific episodic associations occurring between temporally adjacent relevant events can account for performance costs in adaptive decision making, in addition to what is accounted for by proactive goal-driven processes such as maintenance and representation of relevant goals and intentions in WM. The results showed that both accounts explain part of the variance in performance on an *AX*-CPT task, whereas neither of the accounts can explain all the data on its own.

The goal-driven account explains performance costs in terms of top-down biasing exerted by task instructions and by stimulus information held in working memory or by a failure to reactivate the currently relevant information to overcome a response bias. In contrast, the binding account asserts that context cue, probe stimulus, and response information are bound together by temporal coupling during a task. This episodic binding influences performance on future trials in the task because previous associations have to be overcome when the current situation asks for different behavior. Crucially, according to the goal-driven account, the biasing influences of context information will occur regardless of the precise combination of events on previous trials. Our modified *AX*-CPT allowed us to directly test the predictions of the goal-driven account and binding account against each other in *AY* and *BX* trials.

The current study indicates that performance costs in an adaptive decision making task like the *AX*-CPT are well captured by the goal-driven account. Performance on *AY* trials was associated with pronounced costs (slower and less accurate responses) compared to target trials (*AX* trials). Yet, pronounced costs on BX_b trials compared to *AX* or *BY* trials most likely result from a category-based association between *X*-probe and the target response, and were not predicted by the goal-driven account. However, this finding could be explained by the context processing model (Braver & Barch, 2002; Braver et al., 1999, 2001): *X* probes are more often presented with an *A* than with a *B* cue, which will induce a tendency to give a target response to all *X*-probes (both X_a- and X_b-probes, although this tendency is assumed to be stronger in X_a- than X_b-probes). A similar explanation could be given by the binding account, although we originally did not predict costs on BX_b trials. When we assume though that bindings can also occur at a more abstract level instead of a stimulus-specific level (i.e. between cue (case), target response, and abstract features of the probe (gender), such as in BX_b trials), there will be some binding costs in BX_b trials arising during unbinding or rebinding of these abstract features. This would be in line with the feature integration account (Hommel, 2004).

Moreover, the experiment revealed that additional variance in *AY* costs is explained by a stimulus-specific binding account; part of the differences in performance on several *AX*-CPT trial types (*AY*) can be explained only in terms of item-specific bindings, created between cue and probe stimuli during the experiment. That is, the performance costs associated with *AY* trials were more pronounced on trials in which the cue was previously associated with a specific *X*-probe (A_xY) compared to A_yY trials (without any previous association of the cue with a particular *X*-probe). Based on a goal-driven account, it was not predicted that A_x- and A_y-cues would differentially affect performance, because the stimulus-specific information was not explicitly task relevant. Stimulus-specific effects in A_xY and A_yY trials can however also be integrated with the context processing model (Braver & Barch, 2002; Braver et al., 1999, 2001): stimulus-specific A_x-cues were strongly associated with the target probe, while others (A_y-cues) were not. Stimulus features could be considered to provide a subcontext and thus bias performance.

Furthermore, performance costs associated with *BX* trials were more pronounced on trials in which the probe was previously associated with a specific *A*-cue (BX_a) compared to BX_b trials (without any previous association of the probe with a particular *A*-cue). However, this was expressed only in the accuracy data of Experiment 1, while

Experiment 2 did not reveal any binding-related performance costs in *BX* trials. How could we explain this dissociation between binding effects in *BX* and *AY* trials?

First, the *B*-cue was very predictable in terms of response choice, which may have resulted in fast response times on both BX_a and BX_b trials (a floor effect). If the required response becomes less predictable after a *B*-cue, probe information may become more relevant to the decision and thereby affect performance. We found support for this suggestion in a previous behavioral study (Van Wouwe, Band & Ridderinkhof, 2005) in which cue-interpretation depended on probe information, that is, the probe determined whether a cue would be labeled as target (*A*-cue) or nontarget (*B*-cue). With these conditions the *B*-cue becomes inconclusive. Thus, probe information (both category- and stimulus-specific information) is relevant and necessary to make a decision, which may increase attention for category (i.e., gender) and stimulus-specific aspects (i.e., individual face) of the probe. As expected, this yielded an increase of *BX* binding costs, but a reduction of *AY* binding costs. In the current study, however, the cue already induced a strong response tendency; therefore the priming effect of features associated with the cue may be enhanced compared to the probe associated information.

Second, category information may have been more important for decision making in the current task (i.e., male or female face) than stimulus-specific information (i.e., the individual person). Thus, there may have been no need to process this stimulus-specific information anymore, which explains why it did not result in additional performance costs.

Relationship to other studies

Our findings are consistent with other work demonstrating the role of both episodic bindings and goal-driven biases to explain behavioral costs (for a review see Egner, 2007; Verguts & Notebaert, 2008). Performance costs in tasks involving negative priming, task switching and successful response inhibition were previously exclusively attributed to top-down control operations. Recently, however, they have also been explained in terms of binding effects; competing information is reactivated as a result of a retrieved episodic binding that was created on a previous trial between stimulus and response in negative priming tasks (for a review see Tipper, 2001), between stimulus and task during task switching in a word-picture Stroop task (Waszak et al.,

2004) or between stimulus and stop signal in a stop-signal task (Verbruggen et al., 2008) and thereby biases performance on the current trial. Along a similar line of reasoning, the role of conflict monitoring in control could be discussed as well. Mayr et al. (2003) reported that the conflict adaptation effect in a Flanker task is due to repetition of specific stimulus episodes and does not necessarily involve monitoring response conflict. Similarly, Crump, Vaquero and Milliken (2008) proposed that on-line control adjustments during task performance can be initiated not only by a conflict-monitoring mechanism in control processes, but also by the retrieval of episodic memory traces consisting of stimulus-response or context information. It is even advocated that bindings between stimuli and responses might be used by a conflict-monitoring system to indicate the need for control on future trials (Verguts & Notebaert, 2008). That is, if both stimulus and action features are repeated between the current and the previous event there is no conflict signal and thus no need for increased control. Other studies also indicate that conflict-driven control may be applied at different levels, from global task level to item-specific control (Blais, Robidoux, Risko, & Besner, 2007; Egner, 2008).

Consistent with the current behavioral experiments, providing support for the role of top-down control as well as episodic bindings in decision making, a recent neuropsychological account pointed out that these processes may be mediated by different brain areas. Braver, Gray, and Burgess (2007) proposed a conceptual framework that accounts for variations in cognitive control, the Dual Mechanism of Control (DMC) theory, differentiating the importance of both proactive and reactive mechanisms in flexible adaptive behavior. Reactive control involves information processing driven by the latest incoming information; retrieval of context information previously associated with the probe (engaging either medial temporal lobe and hippocampus or posterior brain areas). Similarly, it can be argued that when a feature of an encoded event is encountered on a subsequent occasion, reactivation of the associated features from a previously created event file may also engage reactive control, especially when relevant features mismatch between the current and the previous event. Additionally, reactive control involves resolving possible interference between co-activated responses or correcting erroneous response tendencies (implemented by the anterior cingulate cortex). Proactive control refers to the goal-driven processes that affect decision making to override potentially distracting information, like context processing, and engages the dorsolateral PFC. The DMC theory predicts that depending on individual differences in brain activity in these areas, participants more efficiently apply proactive and reactive control during performance (Braver et al., 2007).

Future research is needed to delineate the role of episodic bindings with more precision, for instance with respect to differential effects of stimulus-stimulus versus stimulus-response binding. In addition, further research is needed to distinguish the relative contribution of episodic bindings in adaptive behavior with modulations in top-down control in populations who are less efficient in applying top-down control, such as older adults or patients with attention deficit hyperactivity disorder. For example, the differential effects of aging on A_xY vis-à-vis A_yY trials compared to *AX* vis-à-vis *AY* trials may shed light on the contribution of feature binding versus context processing.

Conclusion

Adaptive decision making behavior is affected not only by top-down, goal-driven processes but also by the implicitly learned associations between features of a previous event. In some decisions with rapidly changing environmental demands, a goal-driven bias may hamper performance, which can be overcome by applying increased control. However, this top down bias is regulated more efficiently when the specific stimulus is presented in the same context it was previously associated with, compared to when it is presented in a new and unusual context. Responding to stimuli in their real-life context typically involves processing uniquely identifiable cues and probes and a strong correlation between the occurrence of cue and probe. Cue-probe associations form the basis of habit formation, and everyday action slips can in majority be attributed to responding in a habitual way to a stimulus that is presented in a different context than usual (Reason, 1990).