The drive to control : how affect and motivation regulate cognitive control

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8

Task Difficulty and Conflict Adaptation

> "Face a mirror, look at your eyes and invent a mathematical problem, such as 81 times 17. Try to solve the problem and watch your pupil at the same time (…) After a few attempts, almost everyone is able to observe the pupillary dilation that accompanies mental effort."
>
> Daniel Kahneman (1973)

This chapter is based on:

van Steenbergen, H., Band, G.P.H., & Hommel, B. (in preparation). Dynamic control adaptations depend on task difficulty: Evidence from behavior and pupillometry.

Abstract

Sequential modulation of congruency effects in conflict tasks show that cognitive control and effort quickly adapt to changing task demands. We investigated how this behavioral congruency-sequence effect interacts with different levels of task difficulty in a flanker and a Stroop task. In addition, online measures of pupil diameter were used as a physiological index of effort mobilization. Consistent with the notion that task difficulty increases effort mobilization up to a certain limit, dynamic conflict-driven adjustment in behavior was observed only if task difficulty was moderate, whereas congruency effects in behavior and pupil dilation were unaffected. Furthermore, high difficulty levels induced a conflict-driven reduction in pupil dilation, presumably reflecting a physiological marker of mental overload.

Introduction

In a constantly changing environment, cognitive control helps to adaptively respond to task demands. Paradigms such as the flanker task (Eriksen & Eriksen, 1974) and the Stroop task (Stroop, 1992) have been designed to probe cognitive control processes. In the flanker task, for example, people respond to a central target while ignoring flanking distracters. The reaction-time difference between trials with target-congruent and -incongruent flankers has been called congruency effect and been considered a measure of sustained cognitive control. On the other hand, dynamic adjustments in control are reflected in trial-to-trial adaptations. This sequential effect typically shows that the congruency effect on the current trial is reduced when it follows an incongruent as compared to a congruent trial (Gratton et al., 1992; Greenwald & Rosenberg, 1978).

According to the conflict monitoring theory, the congruency-sequence effect occurs because incongruent trials evoke response conflict, which triggers control improvements and thus reduces interference on subsequent trials (Botvinick et al., 2001). Indeed, numerous studies have found evidence for this so-called conflict-adaptation effect, an adaptation that has been demonstrated across flanker, Stroop, and Simon tasks (for a review, cf. Egner, 2007). Accumulating neuroimaging data has demonstrated a possible neural mechanism involving the medial prefrontal cortex as a conflict monitoring system that helps to adapt control by enhancing task-goal representations in more lateral prefrontal areas (e.g., Egner & Hirsch, 2005; Kerns et al., 2004).

Although the congruency-sequence effect typically is investigated in the context of the conflict monitoring theory (Botvinick et al., 2001), it probably reflects a more general effect that Ach and colleagues have coined the 'difficulty law of motivation' (Ach, 1935; Hillgruber, 1912). According to this law, increasing the difficulty of a task automatically makes people to try harder. That is, the amount of mental effort –here defined as the mobilization of energy resources to carry out behavior (Gendolla & Richter, 2010) – invested in the task is thought to be proportional to the level of perceived task difficulty (cf. Kahneman, 1973; Brehm & Self, 1989). This increased mental effort, in turn, may also improve goal-directed behavior as measured in reaction times. Although the majority of the available studies have provided physiological and self-report evidence for effort mobilization in difficult situations (for reviews, see Gendolla, Wright, & Richter, 2011; Wright & Kirby, 2001), a recent study by Dreisbach & Fischer (2011) has shown that adjustments in effort mobilization can also be observed in behavior. In that study, sequence effects in reaction times were observed in a perceptual fluency task using different levels of task difficulty, demonstrating that sequential behavioral adaptation can occur even in the absence of conflict.

The aim of the current study is to investigate how behavioral congruency-sequence effects in conflict tasks interact with different levels of task difficulty. Although – as outlined above – conflict-driven improvement of control is likely to reflect a momentary increase in effort driven by the difficulty of the previous trial, it is important to understand what happens if difficulty further increases. Given the limited nature of processing resources, one would expect that task difficulty can increase effort mobilization only up to some upper limit, after which it reaches asymptote. Likewise, dynamic conflict-driven increases in effort can only occur if there is some room left for improvement. In other words, conflict adaptation may only occur in cases where overall task difficulty is not too high. The present study put this prediction to empirical test.

A first indication that congruency-sequence effects indeed become smaller when resources come close to their limits has been provided by two recent studies. Comparing Simon-task performance under single and dual-task situations, Stürmer and colleagues (Sturmer, Seiss, & Leuthold, 2005) observed smaller congruency-sequence effects in the dual-task context, indicating that the secondary task may have consumed resources needed for conflict-driven improvements in control. In another study by Fischer and coworkers (Fischer et al., 2008), processing demands and response conflict were manipulated within the same trial, using a numerical judgment task in the context of a Simon paradigm. Consistent with a limited resources account, difficult number judgments reduced the subsequent congruency-sequence effect in Simon performance.

The present study aims to find evidence for task-difficulty effects on cognitive control adaptations in a series of three experiments. In Experiment 1 and 2, we compared how task-demand differences between a Stroop and a flanker task may account for the size of conflict-adaptation effects observed. In Experiment 3 an explicit manipulation of task difficulty was used to further investigate the possibility of a difficulty-driven reduction in the congruency-sequence effect.

Experiment 1: Re-analysis of Van Steenbergen et al. (2010)

In a first attempt to test whether demand differences between tasks can account for differences in conflict-adaptation effects, we re-analyzed an earlier published data set (van Steenbergen et al., 2010) by comparing congruency-sequence effects as a function of the level of task demands participants reported. Given that increased task difficulty may increase effort mobilization up to its limits, we expected that no further improvements in cognitive control by previous-trial conflict will be observed under conditions of high task difficulty. That is, we predicted that a task that is associated with high task demands may show smaller congruency-sequence effects.

Methods

For detailed methods, see van Steenbergen et al. (2010).

Participants

Ninety-eight students participated either for payment or course credits (18-30 years old; 24 males; 11 left-handed). Data from seven participants were excluded from analyses because of response omissions on more than 20% of the trials (2), chance level task performance (3), or incompliance with instructions (2). Data were pooled across four different mood induction groups, as the mood conditions were irrelevant for the purpose of the current study.

Tasks

Two variants of a classic cognitive-control paradigm were used to measure conflict adaptation. An adapted version of the flanker task (Eriksen & Eriksen, 1974) consisted of centrally presented target stimuli which were vertically flanked on either side by two identical response-congruent or response-incongruent stimuli. An adapted version of the Stroop task (Stroop, 1992) consisted of a column of five identical stimuli presented in response-congruent or response-incongruent ink colors. Flanker and Stroop stimuli were carefully matched by using sets of Dutch color words. Each task used a counterbalanced unique set of four words. Two of these stimuli were mapped to a left hand response, and the other two stimuli were mapped to a right hand response.

E-prime software was used for stimulus presentation and response recording. All trials started with a fixation cross (randomly varying intervals of 800, 1000, or 1100 ms), followed by the stimulus, which was presented until response registration or, in the case of omission, for 1500 ms. In half of the trials the stimuli would call for different responses (Incongruent [I] condition; e.g., the word “green” surrounded by the words “yellow” in the flanker task and the word “blue” printed in red in the Stroop task) whereas in the other half identical target and distracter dimensions would call for the same response (Congruent [C] condition; e.g., the word “green” surrounded by the words “green” in the flanker task and the word “blue” printed in blue in the Stroop task). All trials were presented in an unconstrained random sequence. Stimuli appeared in lower-case in Arial bold font (3.5 cm wide and 5.4 cm high) and were presented on a grey background. Flanker stimuli used black ink color. Participants viewed the stimuli on a 17” monitor from about 60 cm.

Procedure

Instructions emphasized both speed and accuracy. Following 16 practice trials, and a 10-minute mood induction, participants performed a flanker and a Stroop task block (in counterbalanced order), which were repeated after a short 3-minute mood booster. A textual reminder of the stimulus-response mapping was shown for 15 seconds before the start of each of the four blocks of 72 trials. At the end of the experiment, participants evaluated the flanker and Stroop task in terms of weariness, unpleasantness and difficulty on a 6-points scale.

Results

Subjective ratings

Task difficulty ratings showed that the Stroop task was associated with higher demands than the flanker task (4.1 versus 3.7; t(90) = 2.6, p < .05). Weariness and unpleasantness scores were not different for the tasks (t(90)s < 1.6, ps > .12).

Behavioral results

The first trial of each block (1.4%) and trials not complying with the outlier criterion (2 SDs; 4.7%) were excluded from all analyses. ANOVAs on correct Reaction Time (RT) data revealed significant basic congruency effects for both the flanker task (31 ms; F(1,90) = 137.9, p < .001) and the Stroop task (35 ms; F(1,90) = 71.9, p < .001) confirming that both paradigms can reliably measure cognitive control. However, as Figure 1A shows, a congruency-sequence effect, i.e., a reduction of the congruency effect following conflict, was only found for the flanker task (21 ms; F(1,90) = 17.2, p < .001) but not for the (more difficult) Stroop task (7 ms; F(1,90) = 1.4, p > .2). Accuracy data confirmed the basic congruency effects for the flanker task (2.5%; F(1,90) = 22.3, p < .001) and the Stroop task (2.5%; F(1,90) = 18.5, p < .001). There was a trend for a congruency- sequence effect in the flanker task (2.0%; F(1,90) = 3.68, p = .058). In addition to the congruency-sequence effect in the flanker task, participants showed a tendency to slow their response following conflict (F(1,90) = 11.4, p < .005) (cf. Ullsperger, Bylsma, & Botvinick, 2005).

Discussion

Experiment 1 provides initial support for the hypothesis that task difficulty may be an import factor that accounts for reduced congruency-sequence effects: a Stroop task that was reported to be more demanding yields less conflict adaptation than a matched version of the flanker task. That is, while a reliable congruency-sequence effect was observed in the flanker task, the much smaller effect observed in the Stroop task was not statistically significant, despite the large sample (N = 91).

Experiment 2

Even though Experiment 1 provided initial evidence for task-difficulty effects on conflict adaptation, these data were pooled over several mood induction groups which produced different adaptation effects in the earlier published study (see van Steenbergen et al., 2010). It might thus be argued that the absolute size of conflict-adaptation effects cannot be generalized to emotionally neutral situations. This motivated us to design a replication study.

In addition, the follow-up study recorded pupillary dilation to provide a measure of effort mobilization (cf. Kahneman, Hess & Polt 1964). Although pupil size is also determined by other variables, it has been repeatedly shown that task-related pupil dilation systematically increases as a function of task difficulty or processing load and thus “provides a powerful analytic tool for the experimental study of processing load and the structure of processing resources” (Beatty, p 291 1982; Beatty & Lucero-Wagoner, 2000). Interestingly, when task demands overload the resources, no further dilation occurs and dilation may either reach asymptotic value or decline (Cabestrero, Crespo, & Quiros, 2009; Granholm & Steinhauer, 2004; Peavler, 1974; Poock, 1973). The decline in pupil diameter under conditions of mental overload exclusively occurs when people keep trying to work on the task (Granholm, Asarnow, Sarkin, & Dykes, 1996).

In the context of cognitive control tasks, numerous pupillometry studies have already shown that incongruent Stroop trials increase pupil dilation (Brown et al., 1999; Siegle, Steinhauer, & Thase, 2004; Laeng, Orbo, Holmlund, & Miozzo, 2011), which is consistent with the central assumption that incongruent trials, like other difficult situations, automatically recruit effort. Given that behavioral congruency effects are observed across different paradigms, flanker tasks may produce similar congruency effects on dilation as has been observed in Stroop tasks. However, it is not clear yet how trial-to-trial adaptations are related to effort recruitment on a temporal scale (cf. Scherbaum, Fischer, Dshemuchadse, & Goschke, 2011). Whereas the original computational conflict-monitoring model suggests that conflict from a previous trial starts to recruit effort in the subsequent trial (across-trial adaptation; Botvinick et al., 2001), other models suggest that the adaptation of control may already start to develop within the previous conflict trial itself (within-trial adaptation; e.g., Brown, Reynolds, & Braver, 2007). According to this within-trial adaptation account, conflict adaptation in the current trial is mainly due to a carryover of the adjusted control state from the previous trial. Although recent findings from frequency-tagged EEG responses (Scherbaum et al., 2011; cf. Goschke & Dreisbach, 2008) indeed support this within-trial adaptation account, the pupil dilation signal probably is too slow to accurately index such subtle effort-related adaptation within the previous trial. On the other hand, if conflict adaptation mainly stems from across-trial adaptation (Botvinick et al., 2001), pupil dilation may shown an overall increased dilation in the current trial after conflict in the previous trial. Task difficulty manipulations that reduce adaptation may then decrease this conflict-driven dilation increase in the subsequent trial.

In order to test the effects of task difficulty on sequence effects in cognitive control and effort mobilization, we conducted two new experiments that included a flanker and a Stroop task while pupil data were acquired during task performance. Experiment 2 included a flanker and a Stroop task similar to those used in Experiment 1. We expected to replicate the behavioral finding that, in comparison to the Flanker task, increased task demands in the Stroop task lead to smaller or absent conflict-adaptation effects. Pupil dilation data were acquired to explore sequential effects in effort mobilization.

Methods

Participants

Twenty-eight healthy right-handed Dutch students participated either for payment or course credits (18-30 years old; 7 males). All participants indicated not to use medication (other than anti-conception pills) and were not color blind. Four participants were excluded from analysis because of technical problems during the data acquisition. After initial data screening, two other participants were excluded because of random performance in one or more of the task blocks.

Tasks

The flanker and Stroop tasks were identical to those used in the pilot study with a few exceptions. First, the Stroop task only included one stimulus rather than a column of five identical stimuli in order to prevent potential dilution-effect confounds (cf. Kahneman & Chajczyk, 1983). Second, both tasks used a fixed set of color words in order to match Stroop ink color luminance levels. To specify, the flanker task always used the words “brown”, “gray”, “yellow”, and “red” whereas the Stroop taks always used the words “purple”, “green”, “orange”, and “blue” (all words were presented in Dutch translations). Isoluminant ink colors from the Teufel colors set were used for the Stroop task (Teufel & Wehrhahn, 2000) whereas the flanker task stimuli were printed in black. Finally, in order to avoid pupil light reflexes produced by stimulus presentation (cf. Beatty & Lucero-Wagoner, 2000) a scrambled picture of the average stimulus was used as a baseline fixation stimulus (for both tasks separately).

Procedure

After informed consent was given, participants were seated in a dimly lit room where the eye tracker was calibrated. Following a data quality check, participants performed 28 practice trials for both tasks which were repeated until they sufficiently learned the task to start the experiment proper. Flanker and Stroop trials were presented in 12 alternating blocks (in counterbalanced order). Before each block started, a self-paced textual reminder of the stimulus-response mapping was shown for a maximum of 15 seconds. Each block consisted of 36 consecutive fast test trials (see under Tasks) and 18 consecutive filler trials with a constant inter-trial interval of 4 seconds (test and filler sequence in random order). For both the flanker and Stroop task, 216 test trials were available for sequential analyses of reaction time and pupil dilation. The 108 filler trials were used to validate the timing of the pupil dilation response in the short test trials.

Following each block, participants received accuracy feedback about their performance in a line graph showing their accuracy per block over time. Feedback was given for the flanker and Stroop task separately. Participants were required to make errors within a target range of 5-10%, and if the participant reached this target they received positive feedback which still encouraged both speed and accuracy. If the error rate dropped below 5%, participants received the following text feedback: “You are not doing your best. Please increase speed. You are allowed to make more errors.” If the error rate exceeded 10%, participants received the following text feedback: “You are not doing your best. You are making too many errors. Please improve accuracy but keep responding fast.” A reminder of the feedback given earlier was provided again at the start of the next task block. Visual feedback was verbally reinforced by the experimenter. Short self-paced breaks (for a maximum of 30 seconds) were provided following each pair of two blocks. Participants had a fixed 1-minute break halfway the experiment.

Pupil data acquisition and analysis

Pupil diameter was recorded at 60 Hz using a Tobii T120 eye tracker, which is integrated into a 17-inch TFT monitor. Participants were seated at a distance of approximately 60 cm from the monitor. Pupil data were processed and analyzed using custom-made macros programmed in Brain Vision Analyzer. Artifacts and blinks as detected by the eye tracker were corrected using linear interpolation. Trials including extremely unreliable interpolated values (< 20% data points obtained in the intervals of interest) were excluded from analyses. After visual inspection (see below), pupil dilation was defined as the mean pupil diameter during a 700 to 1300 ms period following stimulus onset. A 200-ms pre-stimulus interval was used as baseline.

Results

All analyses reported for Experiment 2 and Experiment 3 were performed after the following trials were excluded: the first trial of each block, trials following an error, trials with RTs not fitting the outlier criterion (2.5 SDs deviating form the individual condition-specific mean), and trials including unreliable pupil-data interpolations.

Behavioral results

Correct reaction time data are shown in Figure 1B. Replicating our pilot study, both the flanker and the Stroop task yielded a congruency effect ($F(1,21) = 67.7$, $p < .001$, $MSE = 184.9$ and $F(1,21) = 17.1$, $p < .001$, $MSE = 1538.0$), which was modulated by previous trial conflict in the flanker task ($F(1,21) = 9.7$, $p < .01$, $MSE = 213.6$), but not in the Stroop task ($F(1,21) = 0.4$, $p = .52$, $MSE = 456.0$). Error rate data revealed congruency-effects for the flanker ($F(1,21) = 6.1$, $p < .03$, $MSE = .003$) and the Stroop task ($F(1,21) = 4.4$, $p < .05$, $MSE = .001$) but no indications of conflict adaptation for both tasks ($Fs < 1$). These behavioral results replicate the finding in Experiment 1: the Stroop task produced smaller congruency-sequence effects than the flanker task.

Pupil data validation

In order to explore whether effort mobilization as measured by pupil dilation is different between the flanker and the Stroop task, we measured pupil dilation in response to stimulus onset. As is shown in Figure 2A (upper panels), the long-interval filler trials showed a pupil dilation for both the flanker and the Stroop task, which reached its peak value around 1 second after stimulus onset. More importantly, in the same time interval dilations were found for the test trials with the short inter-trial intervals, which validates the analytic approach to define maximum pupil dilation as the mean pupil diameter during a 700 to 1300 ms period following stimulus onset (Figure 2A, lower panels).

The pupil dilation data yielded congruency effects in dilation for both the flanker task (F(1,21) = 14.5, p < .001, MSE = .001) and the Stroop task (F(1,21) = 4.3, p = .052, MSE = .001), irrespectively of the inter-trial interval used (Fs < 1). Thus, pupil diameter could reliably be used as an index of effort mobilization during the test trials with their short inter-trial intervals.

Pupil results

In order to test differential effort mobilization effects on the Stroop versus the flanker task, we analyzed pupil dilation during test trials as a function of congruency of the current trial and congruency of the previous trial, using task (flanker versus Stroop) as an additional within-subject factor. As shown in Figure 1C, both tasks showed more dilation during incongruent trials in comparison to congruent trials (F(1,21) = 10.1, p < .005, MSE = .001). Independent of this, a trend for a main effect of previous-trial congruency was observed: decreases in current-trial dilations were observed when the previous trial was incongruent (F(1,21) = 3.4, p = .08, MSE = .001). This effect was moderated by a significant Task x Previous-Trial Congruency interaction (F(1,21) = 4.7, p < .05, MSE =.0004) showing that the decrease in overall dilation following conflict was only significant in the Stroop task (F(1,21) = 4.9, p < .05, MSE = .001) but not in the flanker task (F(1,21) = .30, p = .60, MSE = .0004). Task did not significantly interact with other (combinations of) factors. Because the Task x Previous-trial Congruency effect was not observed in the preceding baseline interval (F(1,21) = .55, p = .47, MSE = .002), the effect in dilation cannot be attributed to a carry-over effect from a dilation starting in the preceding trial.

Discussion

Experiment 2 replicated the behavioral effect in Experiment 1: conflict adaptation was reduced in the – presumably more demanding – Stroop task in comparison to the flanker task. Pupil data across the flanker and Stroop task showed that incongruent trials produced more dilation than congruent trials. Thus, replicating and extending earlier studies on the Stroop task, both Stroop and flanker conflict induced pupil dilation, which probably reflects conflict-driven effort mobilization.

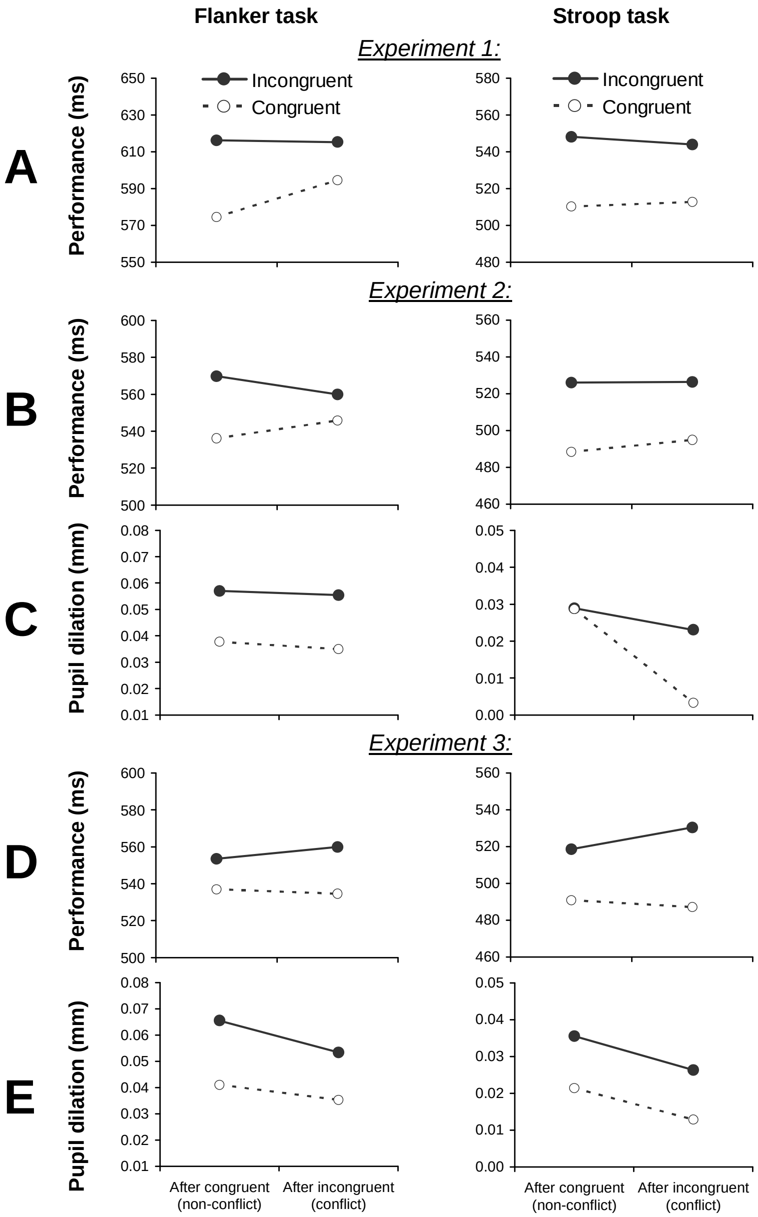

Figure 1. *Flanker task (left column) and Stroop task (right column) performance (**A, B,** and **D**) and pupil dilation (**C** and **E**) across Experiment 1, 2, and 3, as a function of current-trial congruency and previous-trial congruency.*

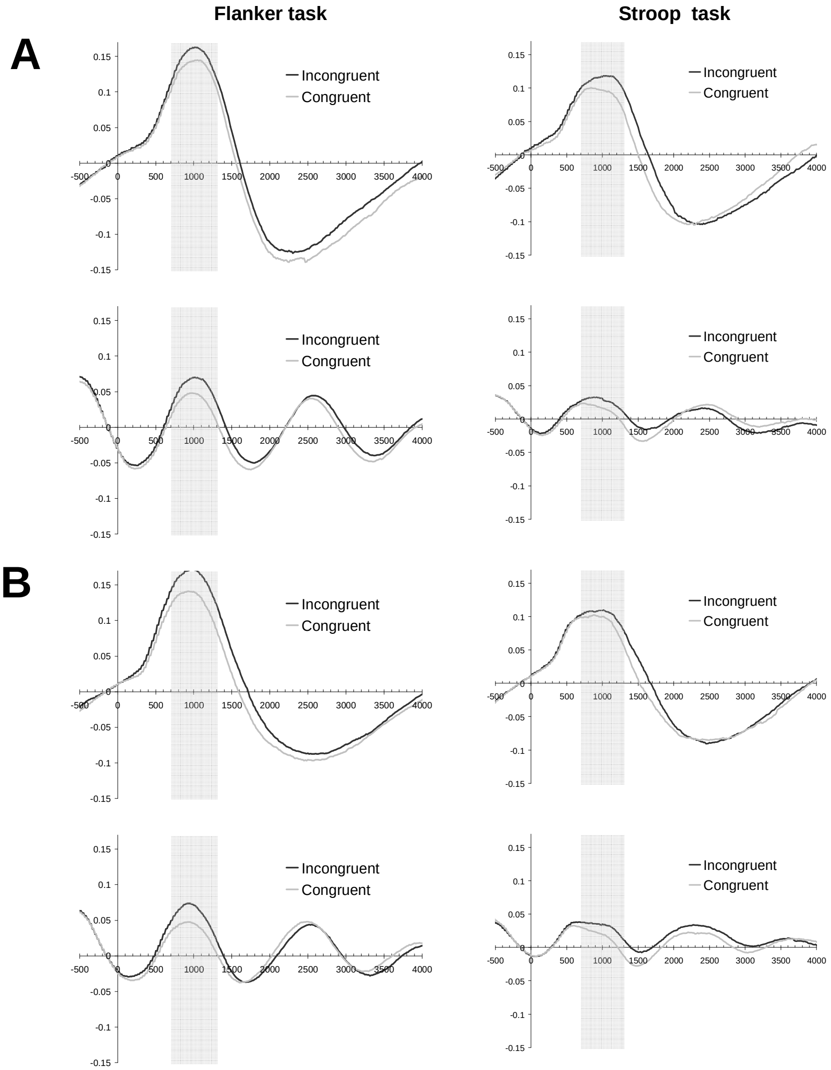

__Figure 2.__ Pupillary response (mm) as a function of time (ms) and current-trial congruency for Experiment 2 (__A__) and Experiment 3 (__B__). Both graphs depict baseline-corrected pupil dilation in the Flanker (left column) and Stroop (right column) task for filler trials (upper row) and test trials (lower row).

Even more importantly, sequential analyses of pupil dilation indicated a main effect of previous trial congruency in the Stroop task, but not in the flanker task. The absence of increased dilation in Trial N after conflict in Trial N-1 for the flanker task, observed in combination with the conflict-adaptation effect in behavioral data, suggests that the behavioral adaptation effect might have been driven by within-trial rather than across-trial adaptation of mental effort. In other words, the conflict-adaptation effect observed at Trial N may reflect a carry-over effect of conflict-driven recruitment of effort that mainly took place within Trial N-1. Interestingly, a conflict-driven reduction in pupil dilation was observed for the Stroop task in the absence of behavioral adaptation. Demand-driven decline of pupil dilation has been reported earlier for overload conditions in other paradigms, including a reaction time task using extreme presentation rates (Poock, 1973) and a digital span recall task using excessive load (Granholm et al., 1996). In line with these findings, the effect observed on pupil dilation may thus represent a physiological marker of resource overload, which in our case is driven by increased task difficulty in combination with the conflict in the previous trial.

Although subjective reports from Experiment 1 support our claim that the Stroop task was experienced to be more difficult than the flanker task, we can only speculate about a possible cause. Importantly, both tasks were carefully matched in terms of stimulus material. That is, both paradigms required a similar manual response to similar verbal information (i.e., color words). Moreover, both the Stroop and the flanker task are thought to induce conflict between relevant and irrelevant stimulus dimensions (Egner, 2008; Kornblum, Hasbroucq, & Osman, 1990), and pupillary responses and behavior confirmed different effects for incongruent trials in comparison to congruent trials. However, the source of this conflict might be different. For example, according the Dimension-Action model (Magen & Cohen, 2007) the Stroop effect is driven by conflict between relevant and irrelevant verbal codes (following the translation from color to word), whereas conflict in the flanker task takes place between relevant and irrelevant stimulus elements in a visual dimension. In addition, Stroop interference stems from two features of the same visual object, whereas flanker interference stems from features of different visual objects (Magen & Cohen, 2002). This may differently impact task demands. Processing the relevant word color in a Stroop stimulus inevitably is accompanied by the processing of the irrelevant color word (Chen, 2003; Duncan, 1984), which may induce task conflict even in congruent trials (Goldfarb & Henik, 2007). In contrast, selective processing of central target relative to surrounding stimuli in the flanker task is simply possible through a spatial narrowing of attention (Laberge, Brown, Carter, Bash, & Hartley, 1991). One or more of these factors might have produced an increase in task difficulty for the Stroop task.*

Nevertheless, it is important to stress that conflict-adaptation effects have been demonstrated in numerous studies on Stroop and Stroop-like effects. To the best of our knowledge, however, the Stroop-like tasks usually reported were not as demanding as the task used in our experiment, which mapped four different stimulus features to two responses. Moreover, previous studies used simple categorization responses and/or a low ratio of incongruent trials (e.g., Kerns et al., 2004), which may well have inflated adaptation effects (cf. Purmann, Badde, & Wendt, 2009). To our knowledge, the few publications that did use a standard color-word Stroop tasks and demonstrate conflict adaptation (Egner & Hirsch, 2005; Naccache et al., 2005) exclusively used a low-demanding two-color version, where participants simply can base their response on the presence or absence of a color change rather than on color identity. Previous work is thus not inconsistent with our claim that increased task difficulty in the Stroop task may eliminate conflict-adaptation effects.

However, given that Experiment 1 and 2 only provide correlational rather than causal evidence for a link between task difficulty and conflict-adaptation reductions, and because it is not the paradigm (Stroop versus flanker) itself thought to be responsible for this effect, Experiment 3 used an experimental manipulation of task difficulty to demonstrate that difficulty effects can occur independently of the particular paradigm.

Experiment 3

In order to increase overall effort, tasks difficulty in Experiment 3 was further increased using a time-pressure manipulation (cf. Kahneman, 1973). A new group of participants performed exactly the same tasks as used in Experiment 2 but with different instructions. Specifically, participants were forced to try improving their

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* The somewhat counterintuitive finding that responses were faster on the Stroop task may also have been driven by quicker processing in phases prior to response selection, e.g., perceptual processes. Moreover, because we used fixed response-stimulus intervals, this may have increased stimulus pacing, which in turn increased task difficulty. Note that faster responses have also been observed as a consequence of the participant's adaptation to higher levels of task difficulty (cf. Washburn & Putney, 2001).

speed over time while maintaining accuracy. We hypothesized that this extra increase in task difficulty should further reduce congruency-sequence effects. That is, in comparison to Experiment 2, we expected to find an additional reduction of conflict adaptation irrespective of the particular task. We recorded pupil diameter in order to find converging evidence for the sequential previous-trial congruency effect observed for pupil dilation (i.e., during the Stroop task in Experiment 2) when behavioral conflict adaptation was absent.

Methods

Participants

Twenty-seven healthy right-handed Dutch students participated either for payment or course credits (18-30 years old; 8 males). All participants indicated not to use medication (other than anti-conception pills) and were not color blind. After initial data screening, three participants were excluded because of random performance in one or more of the task blocks.

Tasks

See Experiment 2.

Procedure

Procedures were identical to Experiment 2, except for the performance feedback and instructions that participants received. Like in Experiment 2, after each block, participants received both accuracy and correct reaction time feedback about their performance in a line graph showing their accuracy and speed per block over time. Feedback was given for the flanker and Stroop task separately. Participants were required to continuously improve speed over time, while keeping errors within a target range of 5-10%. If the participant attained the accuracy target they received positive feedback, which still instructed to further increase speed without reducing accuracy. If the error rate dropped below 5%, participants received the following text feedback: "You are not doing your best. Please increase speed. You are allowed to make more errors." If the error rate exceeded 10%, participants received the following text feedback: "You are not doing your best (or you respond TOO fast). You are making to many errors. Please try as hard as you can and improve accuracy." A reminder of the feedback given earlier was provided again at the start of the next task block. Visual feedback was verbally reinforced by the experimenter.

Pupil data acquisition and analysis

See Experiment 1.

Results

Behavioral results

Consistent with predictions, the increased task difficulty reduced conflict adaptation across tasks (see Figure 1D), as no evidence for congruency-sequence effect was found for the flanker task (F(1,23) = .66, p = .43, MSE = 701.6), whereas the Stroop task even showed a reversal of the congruency-sequence effect (F(1,23) = 7.7, p < .02, MSE = 187.1). Congruency effects (F(1,23) = 27.1, p < .001, MSE = 385.8 and F(1,23) = 13.9, p < .001, MSE = 2166.2) were similar to those reported for Experiment 2. As in Experiment 2, error rate data revealed significant flanker and Stroop congruency-effects (F(1,23) = 6.5, p < .02, MSE = .002 and F(1,23) = 9.6, p < .005) but no indications of conflict adaptation for both tasks (Fs < 2). In addition, the Stroop task produced a previous-trial congruency effect on accuracy (F(1,23) = 4.6, p < .05, MSE = .001), showing an increase in error rate after conflict in the previous trial.

Pupil data validation

As Figure 2B shows, the dilation patterns in Experiment 3 mirrored the effects observed in Experiment 2. Congruency effects were observed in the flanker task (F(1,23) = 26.5, p < .001, MSE = .001) and in the Stroop task (F(1,23) = 4.0, p = .059, MSE = .002), irrespectively of the inter-trial interval used (Fs < 1).

Pupil results

As shown in Figure 1E, both tasks caused more dilation to incongruent than to congruent test trials (F(1,23) = 16.3, p < .001, MSE = .001). Independent of this, previous-trial congruency also influenced current-trial dilations: decreases in dilation were observed when the previous trial was incongruent (F(1,23) = 8.8, p < .01, MSE = .0004), irrespectively of task type (F < 1).

Discussion

As expected, conflict-adaptation effects in Experiment 3 were eliminated for both tasks when performed under conditions of increased task difficulty using time pressure. Standard congruency effects in RT and pupil dilation confirmed that these tasks still induced conflict and effort mobilization. Moreover, as observed for the Stroop task in Experiment 2, the absence of behavioral adaptation in both tasks was accompanied by a conflict-driven reduction in pupil dilation in both tasks.

General Discussion

We provided converging evidence for task-difficulty effects on dynamic control adaptations in three experiments. Experiment 1 and 2 showed that a more difficult Stroop task produced smaller congruency-sequence effects than a less demanding flanker task (see Figure 1A and 1B). Experiment 3 showed that, when task difficulty was manipulated experimentally, these congruency-sequence effects were further reduced for both tasks (see Figure 1D). Altogether, our behavioral findings support our prediction that extreme task difficulty put effort mobilization at its limits, leaving no room for further improvements in cognitive control by previous-trial conflict. As a result, no conflict-adaptation effects were observed in conditions of high task difficulty across three experiments.

In addition, Experiment 2 and 3 demonstrates that pupillary measures provide an interesting tool to index effort mobilization in cognitive control paradigms. Although a few studies already have shown pupil dilation increases to incongruent Stroop trials (Brown et al., 1999; Siegle et al., 2004), we demonstrated (see Figure 2) that this congruency effect occurred independently of the specific paradigm used (i.e., both in the Stroop and the flanker task) and occurred even during fast trial pacing (inter-trial intervals around 1.5 seconds).

Apart from this methodological contribution, pupil data also provided additional insight in how and when difficult situations may automatically trigger effort mobilization. Firstly, behavioral conflict adaptation was not reflected by a temporary increase in effort in the subsequent trial (Figure 1C, left figure), which suggests that conflict-driven mobilization of effort mainly takes place earlier – presumably within the previous conflict trial itself (Scherbaum et al., 2011) rather than across trials (Botvinick et al., 2001). Secondly, during difficult task conditions in Experiment 2 (Figure 1C, right figure) and Experiment 3 (Figure 1E) where no conflict adaptation was observed, pupil dilation data showed a conflict-driven drop of dilation, most likely a physiological marker of mental overload (cf. Granholm et al., 1996). Taken together, behavioral and pupil data reinforced our interpretation why conflict adaptation did not occur during high levels of task difficulty: subjects spent maximum effort already. Rather than being adaptive, additional conflict thus may simply overload the cognitive system under these conditions.

One important aim for future studies is to further test the impact of task difficulty at the most extreme levels. As has been suggested by the motivation intensity theory (Brehm & Self, 1989; Brehm, Wright, Solomon, Silka, & Greenberg, 1983) effort mobilization is proportional to task difficulty as long as success is viewed as possible and worthwhile. In cases where a demand is perceived as too high to actively cope with, effort mobilization may drop. In other words, there might exist an inverted-U relationship between task difficulty and effort mobilization (Gendolla et al., 2011). Thus far, evidence for the motivation intensity theory has mainly been provided by cardiovascular and subjective measures of effort, and it is an important aim for future studies to further investigate the link with behavioral measures of loosened control after extreme demands. However, it might actually be speculated that the small reversal of conflict adaptation of Stroop performance under time pressure in Experiment 3 illustrates this drop of effort mobilization driven by previous-trial conflict in a very demanding situation. If this is true, reduced conflict-driven pupil dilation in this situation may well indicate a reduced mobilization of effort in this situation, rather than a physiological signal of mental overload. However, given that the effect was small and not anticipated, future experiments are needed to further investigate this possibility.

An important take-home message of this study is that too difficult conflict tasks may not produce the typical congruency-sequence effect. Our findings explain why some researchers using difficult tasks (e.g., using high incongruent-to-congruent ratios) have failed to observe normal conflict-adaptation effects (e.g., Wendt, Heldmann, Munte, & Kluwe, 2007). Moreover, our work contributes to the cumulating evidence that various factors like trial pacing (e.g., Notebaert, Gevers, Verbruggen, & Liefooghe, 2006), time on task (Mayr & Awh, 2009), incongruent-congruent ratio (Purmann et al., 2009), "correction" for binding effects (e.g., Akcay & Hazeltine, 2007, but see Spape & Hommel, 2008), and type of conflict involved (Verbruggen, Notebaert, Liefooghe, & Vandierendonck, 2006) all may influence the size of congruency-sequence effects. Given that all these factors are likely to change task difficulty and motivation, it as an important future challenge to understand how these factors determine effort mobilization and cognitive control, and which emotional and motivational neural systems are responsible for this modulation.

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