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RESEARCH REPORT

Cognitive Effort Is Modulated Outside of the Explicit Awareness of Conflict Frequency: Evidence From Pupillometry

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Classic theories of cognitive control conceptualized controlled processes as slow, strategic, and willful, with automatic processes being fast and effortless. The context-specific proportion compatibility (CSPC) effect, the reduction in the compatibility effect in a context (e.g., location) associated with a high relative to low likelihood of conflict, challenged classic theories by demonstrating fast and flexible control that appears to operate outside of conscious awareness. Two theoretical questions yet to be addressed are whether the CSPC effect is accompanied by context-dependent variation in effort, and whether the exertion of effort depends on explicit awareness of context-specific task demands. To address these questions, pupil diameter was measured during a CSPC paradigm. Stimuli were randomly presented in either a mostly compatible location or a mostly incompatible location. Replicating prior research, the CSPC effect was found. The novel finding was that pupil diameter was greater in the mostly incompatible location compared to the mostly compatible location, despite participants' lack of awareness of context-specific task demands. Additionally, this difference occurred regardless of trial type or a preceding switch in location. These patterns support the view that context (location) dictates selection of optimal attentional settings in the CSPC paradigm, and varying levels of effort and performance accompany these settings. Theoretically, these patterns imply that cognitive control may operate fast, flexibly, and outside of awareness, but not effortlessly.

Keywords: Cognitive control, context-specific proportion congruence, awareness, effort, pupillometry

It is easy to assume that a conscious intention precedes an effortful action. For example, attempts to prevent or minimize distraction, such as interrupting a meeting to close an office door or searching through one's purse to silence a cell phone, seem to reflect a conscious decision to engage physical effort. Similarly, it is commonplace to assume that a conscious intention precedes efforts to cognitively minimize distraction: we "try" to focus harder, concentrate, or pay attention (see Hommel, 2007, for challenges to this assumption). That is, subjectively it may feel as if cognitive efforts to limit the influence of distractors on performance are mediated by intentions of which we are consciously aware. Indeed, conscious intentions have been a major force in theories of cognitive control since their earliest incarnations (Ach, 1910/2006; Norman & Shallice, 1986; Posner & Snyder, 1975; Shiffrin & Schneider, 1977), often spoken of as "strategic" or "willed" influences on behavior (Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982).

In light of the assumption that conscious intentions lead to the effortful control of attention, an intriguing set of findings has emerged in the cognitive control literature. These findings illustrate a modulation of attentional control in response to varying task demands in the absence of conscious awareness of these demands (see Bugg & Crump, 2012, for review). Further examination of this pattern presents a unique opportunity to test two competing ideas concerning the relationship between conscious intentions and effort: (a) the modulation of controlled attention occurs outside of conscious awareness of task demands and is thus not accompanied by modulations of effort, or (b) the modulation of controlled attention occurs outside of conscious awareness of task demands but is nonetheless accompanied by modulations of effort. We begin by highlighting the most relevant finding, which sets the stage for the current study, and then discuss how pupillometry may be used to shed light on the relationship between control, effort and conscious awareness of task demands.

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The Context-Specific Proportion Compatibility Effect

The compatibility effect is the slowed responding and sometimes more errant performance on incompatible (e.g., >><>>) relative to compatible (e.g., >>>>>) trials in a flanker task in which the goal is to press a key corresponding to the central arrow while ignoring the flanking arrows. Most relevant to the current study is a pattern termed the context-specific proportion compatibility (CSPC) effect (Corballis & Gratton, 2003; Crump, Gong, & Milliken, 2006). The CSPC effect refers to the modulation of the compatibility effect as a function of the relative frequency of response conflict within a given context.[1] One common contextual manipulation that produces robust CSPC effects is that of location. The magnitude of the compatibility effect is reduced in a mostly incompatible location (i.e., 25% compatible trials) when compared with a mostly compatible location (i.e., 75% compatible trials; Bugg, 2014; Corballis & Gratton, 2003; Crump et al., 2006; Crump & Milliken, 2009; Crump, Vaquero, & Milliken, 2008; King, Korb, & Egner, 2012; Vietze & Wendt, 2009; Weidler & Bugg, 2016; Wendt, Kluwe, & Vietze, 2008; Zurawska vel Grajewska, Sim, Hoenig, Hernberger, & Kiefer, 2011; see also Fischer, Gottschalk, & Dreisbach, 2014, for a location-based CSPC effect in a task-switching paradigm).

The CSPC effect is observed in spite of the fact that the overall proportion of compatible trials during blocks of the task is 50% and the presentation of stimuli across locations is random. This means that the CSPC effect is not produced by a global strategy (e.g., proactive control; Braver, Gray, & Burgess, 2007) because attempting to uniformly ignore flanker arrows would result in equivalent compatibility effects across locations. Instead, the CSPC effect has been attributed to a fast and flexible control mechanism that operates poststimulus onset (i.e., reactively) in a location-specific fashion (Bugg & Crump, 2012; Crump et al., 2006). According to the episodic retrieval account (Crump & Milliken, 2009), a narrower attentional setting is retrieved upon presentation of a stimulus in a mostly incompatible location (leading to a smaller compatibility effect) whereas a broader attentional setting is retrieved in the mostly compatible location (leading to a larger compatibility effect). Crump and Milliken (2009) found CSPC effects not only for biased (75% and 25% congruent, respectively) stimuli in the mostly compatible and mostly incompatible locations but also for a unique set of stimuli for which proportion compatibility was 50% regardless of the location in which they appeared. The latter finding was important in demonstrating that the attentional settings that are retrieved in response to location cues are abstract, and that the CSPC effect cannot be fully accounted for by the learning of complex associations between locations, distractors, and responses.

The fast and flexible attentional adjustments underlying the CSPC effect challenge classic conceptualizations of cognitive control as a slow-acting and strategic process (for reviews, see Bugg, 2012; Bugg & Crump, 2012; for evidence of a related pattern termed the item-specific proportion congruence effect, see Bugg, 2015; Bugg & Hutchison, 2013; Bugg, Jacoby, & Chanani, 2011; Jacoby, Lindsay, & Hessels, 2003). Accordingly, the CSPC effect has also led researchers to question the extent to which conscious intentions guide cognitive control. To date, the evidence favors an interpretation of the CSPC effect that aligns with Jacoby, Lindsay, and Hessels (2003) oxymoronic concept of "automatic control." Given the characterization of automatic processing as occurring outside of awareness, and as being effortless (Posner & Snyder, 1975; Shiffrin & Schneider, 1977), there are several important implications of this interpretation. One is that controlled processing may occur outside of awareness. A second is that controlled processing may occur without effort. Both imply that the constructs of awareness and effort may be independent of control. Within CSPC studies, there is evidence for the separation of control and awareness (i.e., modulations of control occur independent of awareness; as discussed next), but it remains untested whether control and effort are separable (i.e., whether modulations of control occur independent of effort).

A primary approach to gauging the role of conscious intentions (awareness) in the CSPC effect has been to ask subjects to estimate the percentage of compatible versus incompatible trials for each location following completion of the task (Crump et al., 2006). The rationale is as follows: To the extent that the CSPC effect reflects effortful modulations of attention and these modulations are driven by our conscious intentions to (strategically) narrow versus broaden (relax) attention in mostly incompatible as compared with mostly compatible locations, then participants should be aware of the difference in conflict frequency between the two locations (i.e., the basis on which such conscious intentions would be operating). Across three experiments, Crump et al. (2006) consistently found that participants reported equivalent proportions of compatible trials, 45% to 54% in the mostly compatible and mostly incompatible locations (Crump et al., 2006; for replications, see Crump et al., 2008; Diede & Bugg, 2016). These data have been taken as evidence that the CSPC effect does not rely on the explicit awareness of context-dependent conflict frequency (Crump et al., 2006; Crump et al., 2008; see Reuss, Desender, Kiesel, & Kunde, 2014, for evidence that the CSPC effect also does not depend on conscious awareness of context cues). On the view that the engagement of effort requires conscious awareness of task demands (here, the demands associated with each context), the awareness data additionally suggest it is unlikely that the CSPC effect is accompanied by variation in cognitive effort.

Current Study

The current study investigated this question by examining whether cognitive effort, as measured by the size of the pupil response, is modulated outside of the explicit awareness of context-specific demands for heightened control by tracking participants' eyes during a variant of the CSPC paradigm (Weidler & Bugg, 2016, Experiment 1). Pupillometry entails the passive and continuous recording of pupil size during task performance, and has been successfully utilized as a measure of cognitive effort for over 40 years (Kahneman & Beatty, 1966; also see Laeng, Sirois, & Gredebäck, 2012). In situations of greater task demands, an increase in pupil diameter is found, suggesting pupil size has a close association with cognitive effort. For example, pupil size has been found to be larger on incompatible (relative to compatible) Stroop and Simon stimuli, perhaps due to an effortful focusing of attention caused by experiencing response conflict (Laeng, Ørbo, Holmlund, & Miozza, 2011; Van Steenbergen & Band, 2013; cf. Wendt et al., 2014, for the finding that pupil size is larger following incongruent trials compared to congruent trials in a flanker task). Likewise, tasks that require heightened or sustained control

[1] The CSPC effect also refers to the modulation of congruency effects (i.e., context-specific proportion congruency effect; Crump et al., 2006), as in Stroop paradigms. However, because the present study utilized a flanker paradigm, we use the term compatibility effect throughout.

are associated with greater pupil sizes, such as during response preparation (Moresi et al., 2008) and when preventing gaze from returning to highly salient objects in a visual scene (Mathôt, Siebold, Donk, & Vitu, 2015). An intriguing and theoretically important question is whether the awareness of heightened control demands is critical for the modulation of cognitive effort.

Explicit awareness was gauged using the retrospective self-report measure adopted by Crump et al. (2006; see also Blais, Harris, Guerrero, & Bunge, 2012). Replicating prior findings, in the current study a CSPC effect was observed and participants' estimates of proportion compatibility were about 50% for both the mostly compatible and mostly incompatible locations. If explicit awareness of context-specific task demands is necessary for the differential exertion of cognitive effort across contexts, then no difference in effort, as indicated by pupil response, should be found between locations of different proportion compatibilities. This pattern would coincide with the interpretation of the CSPC effect as illustrating automatic control (Jacoby et al., 2003), and point to the operation of a control mechanism that operates without awareness *and* requires minimal if any effort (e.g., as might occur if representational weights of task relevant features were tonically adjusted over time in a location-specific fashion, and automatically activated by the presentation of a flanker stimulus in a given location).[2]

Alternatively, if modulations of effort occur outside of the explicit awareness of context-specific task demands, then pupil responses may differ between mostly compatible and mostly incompatible locations. One hypothesis was that a greater pupil response would be found in the mostly incompatible location than in the mostly compatible location, indicating greater exertion of effort in order to meet the control demands of the high conflict frequency context (cf. Schouppe, Ridderinkhof, Verguts, & Notebaert, 2014). This hypothesis coincides with the view that the retrieval of the optimal control setting for a given context is cued by the context itself (e.g., Crump & Milliken, 2009) and not by trial type (compatible vs. incompatible) or the interaction of context and trial type. In other words, any flanker stimulus that is presented in the mostly incompatible context should stimulate retrieval of a narrow control setting, and this setting is predicted to be more effortful than the broader (relaxed) setting retrieved in response to the presentation of a flanker stimulus in the mostly compatible context. In addition to the CSPC effect (Proportion Compatibility × Trial Type interaction) that, as already noted, was observed for reaction time (RT), another behavioral outcome was anticipated. Generally slower RTs may be observed in the mostly incompatible location, indicative of an increase in controlled processing compared to the mostly compatible location.

Yet, another potential outcome was that there would be an interaction between proportion compatibility and trial type not only behaviorally but also in the pupil response. This prediction emerges from a consideration of the role of frequency or event learning processes in the CSPC effect (see Crump et al., 2006, for discussion). It is necessarily the case that compatible trials occur more frequently than incompatible trials in the mostly compatible location, and the reverse is true in the mostly incompatible location. Accordingly, it might be predicted that the pupil response would be dependent on stimulus novelty (e.g., infrequent [novel] stimuli might evoke a larger pupil response indicating recruitment of more cognitive effort, and this may be especially true when a higher demand [incompatible] stimulus occurs in a generally lower demand [mostly compatible] context; cf. Kamp & Donchin, 2015). This possibility coincides with computational models that suggest the CSPC effect is the result of increased response caution due to different expectations of experiencing conflict across contexts (King, Donkin, Korb, & Egner, 2012). Alternatively, the interaction might arise if pupil response is dependent on the ease of retrieving responses that are associated with particular stimuli in a particular location (e.g., less effort may be needed to respond to compatible trials in the mostly compatible context than incompatible trials in the mostly compatible context because the compatible trials are more frequent and therefore allow participants to bypass control and simply retrieve the associated response; cf. Schmidt & Besner, 2008). Although these mechanisms may produce interactions that take on slightly different forms, the key point for present purposes is that they predict an interaction between proportion compatibility and trial type in the pupil response.

Method

Participants

Data from 31 Washington University students (19 females; $M_{\text{age}} = 19.3$, $SD_{\text{age}} = 1.2$) were collected and analyzed; one additional participant was tested but excluded due to a recording failure. Participants were required to be right-handed and to have normal or corrected-to-normal vision. Partial course credit was given in compensation for participation.

Apparatus

Pupil measurements were made using an EyeLink 1000 (SR Research, Mississauga, Canada) video-based eye tracker sampling at 1,000 Hz, which records pupil size in pixel units. Stimulus presentation was controlled by Experiment Builder (SR Research, Mississauga, Canada) on a 1,440 × 900 LCD monitor with a 75 Hz refresh rate. Responses were made on a RESPONSEPixx response box (VPixx Technologies, Inc., Saint-Bruno, Canada) that had a central button surrounded by four buttons arranged in a cross shape.

Design and Stimuli

A 2 (Proportion Compatibility: Mostly Compatible vs. Mostly Incompatible) × 2 (Trial Type: Compatible vs. Incompatible) within-subjects design was used. Following Weidler and Bugg (2016), a central location served to anchor the mostly compatible and mostly incompatible locations, with one of these two locations appearing in one corner of the screen (e.g., lower left) and the other appearing in the opposite corner (e.g., upper right) on an imaginary diagonal (see Figure 1). For all participants, the central location was unbiased, presenting 50% compatible and 50% incompatible trials. The mostly compatible location comprised 75% compatible stimuli and the mostly incompatible location comprised 25% compatible stimuli. The bias (proportion compatibility) of the outer locations, and the slope (positive [lower left to upper right] vs.

[2] We thank an anonymous reviewer for this example and recommending we more fully consider this interpretation.

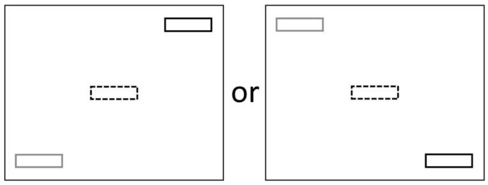

Figure 1. Arrangement of stimulus locations on screen. Gray and black boxes represent biased locations of different proportion compatibilities, while dotted boxes represent unbiased locations (not analyzed). Arrangement of stimulus locations was counterbalanced across participants.

negative [upper left to lower right]), was counterbalanced across participants. The monitor used for the current study had a widescreen 16:9 aspect ratio such that black pillars the height of the monitor appeared continuously on the left and right side of the screen to imitate a 5:4 aspect ratio monitor (as in Weidler & Bugg, 2016).

Following Weidler and Bugg (2016), flanker stimuli were black on a white background, and were composed of seven arrows that could point either up, down, left, or right. On compatible trials, all arrows pointed in the same direction. Hence, there were four possible compatible configurations. On incompatible trials, the central arrow pointed in a direction that conflicted with the flanking arrows. There were 12 possible configurations (e.g., a right central arrow could be surrounded by six left arrows, six up arrows, or six down arrows). All flanker stimuli were 7.6 degrees wide by 1.0 degrees tall. Biased locations at the corners of the screen were 16.9 degrees from a centrally presented fixation cross to the respective target arrow. The fixation cross itself was 0.6 degrees wide by 0.6 degrees tall.

Procedure

Participants began by giving their informed consent and completing a brief demographics questionnaire. Participants then placed their head into a forehead and chin rest anchored 54 cm from the display monitor. They were informed of the importance of keeping their head still, told not to move from the headrest or speak except during breaks, and instructed to return their eyes to a centrally presented fixation cross after they made each response. The eye tracker was then calibrated to measure pupil size and to maintain an average gaze error of 0.5 degrees or less at nine points on screen (maximum error allowance for a single point being 1.0 degree). Participants were then instructed on how to respond to the stimuli using the response box placed directly in front of them. The task was to locate the central arrow within the flanker array and press the button (up, down, left, or right) corresponding to the direction of the arrow (up, down, left, or right, respectively) as fast and accurately as possible. Responses were made with the right index finger, which was rested on the central button on the response box between trials.

After completing 12 practice trials the experimental task began. The task consisted of three blocks of 192 trials with a break allowed in between blocks. Each block was preceded by a drift check to confirm the eye tracker was still accurately calibrated. Each trial began with a 200-ms baseline recording of pupil size, during which a fixation cross appeared centrally. Immediately thereafter, a flanker stimulus was presented, which coincided with the start of a 2,000-ms recording window. The stimulus remained on screen until response, at which point the fixation cross replaced the stimulus. The duration of this recording window ensured that the pupil response was allowed to fully peak before the start of the next trial (see Figure 2). The eye tracker was recalibrated during a break if at any point the participant was seen to have moved significantly or after having failed a drift check.

After completing the computer task, participants were given the post-experiment awareness questionnaire. First, participants' awareness of the difference in proportion compatibility between locations was assessed. Following Crump et al. (2006), they were asked to estimate the percentage of compatible and incompatible trials in the "top portion of the screen" (while assuring estimates summed to 100%), followed by a confidence rating of their estimate on a 9-point Likert scale where 1 = *not at all confident* and 9 = *completely confident*. The same set of questions was asked for the "bottom portion of the screen". Next, they were asked "Did you feel that one portion of the screen was more difficult than the other?" There were four response options: "All portions were equally difficult," "The top portion was more difficult," "The middle portion was more difficult," and "The bottom portion was more difficult." Participants were then debriefed and thanked for their participation.

Preprocessing

Eyeblinks identified by the EyeLink software were corrected using linear interpolation (Chiew & Braver, 2013; Kuchinsky et al., 2013). Baseline correction was accomplished by taking the average pupil size during the first 200 ms of a given trial and subtracting that value from subsequent time points (Laeng et al., 2011). To reduce data for statistical analysis, a given trial's time course was down sampled into 100 ms time bins by averaging the pupil response within each of 23 time bins.

Data Analysis

Reaction times (RT) from the flanker task were analyzed using 2 (Proportion Compatibility) $\times$ 2 (Trial Type) within-subjects ANOVAs. Self-reported estimates of the proportion of compatible and incompatible trials were analyzed with two-tailed one-sample t tests that compared estimates against the actual proportion, and by a paired-samples t test to compare estimates between locations. Paired-samples t tests were also used to compare overall mean RTs between each location. Responses from the subjective difficulty question were analyzed using a 2 (Location: mostly compatible on

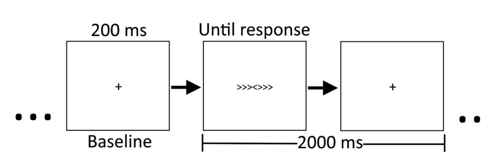

Figure 2. Progression of a single trial. During the baseline recording window, a fixation cross was presented until stimulus onset, which then initiated the 2,000-ms post-stimulus onset recording window. Stimuli remained on screen until response, even if 2000 ms had elapsed. Stimuli not shown to scale.

top or mostly compatible on bottom) × 3 (Response: equally difficult, top more difficult, or bottom more difficult) chi-square test for independence.

Pupil time course data were analyzed using hierarchical linear modeling in R version 3.2.3 using the lme4 (version 1.1–11), lmerTest (version 2.0–30), and multcomp (version 1.4–3) packages (Mirman, 2014; see also Kuchinsky et al., 2013, for similar usage). A two-level no intercept model[3] predicting change from baseline pupil size was specified with a random effect of time varying across task conditions within subjects (see Mirman, 2014). There were four task conditions representing the crossing of proportion compatibility and trial type—compatible trials in the mostly compatible location, incompatible trials in the mostly compatible location, compatible trials in the mostly incompatible location, and incompatible trials in the mostly incompatible location. Each task condition was entered as a fixed effect, while the curves of each time course were modeled using first order (slope), second order (squared), and third order (cubic) natural polynomials on all time terms. By specifying a no intercept model, one curve for each task condition could be modeled within a single regression equation allowing for the interpretation of independent intercepts, slopes, and higher order polynomial effects for each task condition. For example, a model centered at the peak point of a curve would have beta weights associated with an intercept and each of the higher order polynomials (slope, quadratic, and cubic effects). The intercept (zero order) of such a model would estimate the average pupil response at the peak of the curve (i.e., where the model is centered). The slope effect would estimate the slope of the curve at the peak, the quadratic effect would estimate the peakedness of the curve at the peak, and the cubic effect would estimate the relative peakedness of the two deflections of the whole curve (the highest order of a linear model is unchanged by centering point). By independently choosing centering points for each of the four task conditions, relevant contrasts could be established to test the hypotheses. *Model 1* contrasted peak pupil response across task conditions by centering the time terms on the peak pupil response of each curve, thereby testing the primary question of whether pupil diameter is modulated by location context and trial type. Intercept terms were effect coded, and comparisons between curves were made using general linear hypothesis testing in order to test for effects of proportion compatibility, trial type, and the Proportion Compatibility × Trial Type interaction. To preface our findings, only main effects of proportion compatibility and trial type were observed in Model 1. As a follow-up analysis, *Model 2* was constructed to determine whether the main effect of proportion compatibility was evident on context switch trials (i.e., trials that appeared in a new location relative to the previous trial) and context repeat trials. If location cues the effortful retrieval of control settings, then for both context switch and context repeat trials peak pupil response should be larger for the mostly incompatible location than the mostly compatible location (as in Model 1).[4] Finally, an exploratory model was tested after visual inspection of the data from Model 1 suggested that the mostly compatible-incompatible pupil response lagged behind the mostly compatible-compatible pupil response. To test for a lagged pupil response, *Model 3* was centered on the peak response of the mostly compatible-compatible trial curve. Slope terms were effect coded and also compared using general linear hypothesis testing.

Results

Following Weidler and Bugg (2016), the middle unbiased location was excluded from analysis. Because no eye movement was required to respond to the middle location, comparing compatibility effects and pupil responses between the middle unbiased and outer biased locations is confounded with the distance the eyes had to move (for completeness, descriptive statistics for the unbiased location are reported in Table 1).[5] For RT analyses, trials with incorrect responses or trials on which RTs were less than 200 ms or greater than 2,000 ms were eliminated (Bugg, 2015; Weidler & Bugg, 2016), excluding an average of 2.1% ($SD = 2.0$) of trials per participant. Overall error rate was low ($M = 0.02$, $SD = 0.003$) and the analysis of error rates did not contradict the RT analysis; therefore, we report only analyses of RT (see Table 1 for error rates). An alpha level of .05 was used for all inferences. Satterthwaite approximations were used to estimate p values for the beta weights of the linear models (Mirman, 2014).

Behavioral Analyses

A significant Proportion Compatibility × Trial Type interaction was found, $F(1, 30) = 71.29$, $MSE = 298$, $p < .001$, $\eta_p^2 = .704$, due to a larger compatibility effect in the mostly compatible location ($M = 210$ ms) compared with the mostly incompatible location ($M = 158$ ms). This resulted in a 52 ms CSPC effect (see Figure 3). The main effect of trial type was significant, $F(1, 30) = 513.15$, $MSE = 2050$, $p < .001$, $\eta_p^2 = .945$, due to faster RT on compatible ($M = 672$ ms) than incompatible ($M = 856$ ms) trials. The main effect of proportion compatibility was not significant, $F < 1$.

Because the main effect of proportion compatibility can be obscured by the weighted averaging that occurs due to the trial type factor in the omnibus ANOVA, a paired-samples t test was conducted comparing mean RTs that were separately averaged for

[3] Hierarchical linear modeling is preferred over peak-picking ANOVA contrasts for analyzing time course data due to its ability to describe and compare complex continuous auto-correlated data. By centering the model on particular points of a pupil response curve, the technique can return the estimated average response at the centering point, as well as the rate of change at that point (the slope) and the strength of any higher order polynomial effects (quadratic, cubic, etc.). Such information would be lost when doing either ANOVA or area-under-the-curve analyses.

[4] A full Context Switch × Previous Trial Type × Proportion Compatibility × Trial Type model could not be tested due to the number of observations per cell per participant being below 10 in a number of cells, with some as low as two observations. As the critical question for Model 2 was the presence or absence of the main effect of proportion compatibility following a change in location, a Context Switch × Proportion Compatibility model was instead chosen.

[5] With regards to the effect of eye movements on pupil response, the act of rotating the eye either toward or away from the camera affects pupil measurements (Gagl, Hawelka, & Hutzler, 2011). Rotating toward the camera artificially inflates pupil size measurements, and vice versa. The counterbalancing of proportion compatibility across the lower and upper locations controls for this potential confound in comparisons between the mostly compatible and mostly incompatible location. However, comparisons between biased locations and the middle unbiased location are confounded by the influence of this effect.

Table 1
Mean Reaction Times and Error Rates as a Function of Proportion Compatibility and Trial Type

	Mostly compatible		Mostly incompatible		Unbiased	
	Compatible	Incompatible	Compatible	Incompatible	Compatible	Incompatible
Reaction time	663 (94)	878 (128)	688 (99)	848 (112)	567 (90)	660 (114)
Error rate	.13 (.34)	4.81 (4.61)	.20 (.62)	3.01 (2.31)	.07 (.38)	.74 (1.10)

Note. Reaction times are in milliseconds, error rates are percentages. Means are outside of parentheses, standard deviations within.

each location without regard for trial type.[6] RT was found to be slower in the mostly incompatible location (M = 800 ms, SD = 103) compared with the mostly compatible location (M = 708 ms, SD = 99), $t(30) = 14.64$, $p < .001$, $d = 2.63$, 95% CI [79, 104].

Post-experiment Questionnaire Analyses

Estimates of the percentage of compatible trials in the mostly compatible location (M = 49.8%, SD = 14.1) were significantly lower, $t(30) = -9.93$, $p < .001$, $d = 1.79$, 95% CI [−30.34, −19.99], than the correct proportion (75%). Conversely, estimates of compatible trials in the mostly incompatible location (M = 45.1%, SD = 13.0) were significantly higher, $t(30) = 8.62$, $p < .001$, $d = -1.55$, 95% CI [15.33, 24.86] than the correct proportion (25%). Estimates for the two locations did not differ significantly from each other, $t(30) = 1.55$, $p = .133$, $d = 0.28$, 95% CI [−1.52, 11.01]. Confidence was moderately low for both mostly compatible (M = 4.3, SD = 1.5) and mostly incompatible (M = 3.9, SD = 1.4) estimates. The majority of participants indicated that they felt the bottom portion of the screen was more difficult (38.7%), followed by all portions of the screen (32.3%) and the top portion (25.8%), with one participant (3.2%) who answered both "all portions" and "the top portion." No participant chose "the middle portion." Responses were not dependent on the actual location of the mostly compatible location, $\chi^2(2, N = 30) = 2.28$, $p = .320$, Cramer's $V = .275$ (adding the participant who circled two options did not change the conclusions, $\chi^2(3, N = 31) = 3.37$, $p = .338$, Cramer's $V = .330$).

Pupil Analyses

Primary analysis. Parameter estimates for each model are reported in Table 2 (see Figure 4 for grand average pupil responses).

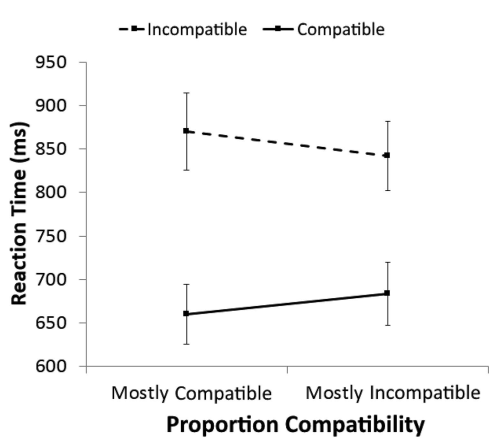

Figure 3. Mean RTs as a function of trial type and proportion compatibility. Error bars represent 95% confidence intervals.

Model 1 was specified to determine if peak pupil response (measured in pixels) differed between conditions. Peaks were identified by visual inspection of the curves, which were affirmed by the slope terms for each curve losing significance at the chosen time bins (see Figure 5).[7] The intercepts of each curve were then contrasted using effect coding, revealing that pupil response was significantly greater for incompatible trials when compared to compatible trials, $M_{\text{difference}} = 86.01$, $SE = 30.98$, $z = 2.78$, $p = .01$.[8] Most important for present purposes, pupil response was greater on trials appearing in the mostly incompatible location compared to the mostly compatible location, $M_{\text{difference}} = 63.54$, $SE = 30.98$, $z = 2.05$, $p = .04$, and the Proportion Compatibility × Trial Type interaction was not significant, $M_{\text{difference}} = 2.56$, $SE = 30.98$, $z = 0.08$, $p = .93$.

Model 2 was next specified to determine if the main effect of proportion compatibility was present on context switch trials and on context repeat trials. Peaks were identified by the same method as in Model 1, with the intercepts effect coded for statistical comparison. A main effect of proportion compatibility was found, $M_{\text{difference}} = 105.70$, $SE = 29.82$, $z = 3.55$, $p < .001$, which was not modulated by a switch in context, $M_{\text{difference}} = 8.01$, $SE = 29.82$, $z = 0.27$, $p = .79$. There was no main effect of context switch, $M_{\text{difference}} = -25.46$, $SE = 29.82$, $z = 0.85$, $p = .39$.

Secondary analysis. Visual inspection of Figure 5, including the centering points determined in Model 1, suggested that the mostly compatible-incompatible pupil response peaked later than (i.e., lagged behind) the mostly compatible-compatible response. The following logic was used to test for a lag effect: If the peak of one curve lags behind the other, centering both curves on the peak of the earlier curve

[6] We thank an anonymous reviewer for suggesting this analysis.

[7] The slope for the mostly incompatible-incompatible trial curve did not lose significance at the peak, likely because of the loss of information that occurred during down sampling. Therefore, the time bin with the lowest slope was chosen as the peak where the model was centered for this condition. To confirm that this choice was appropriate, we examined whether the slope became negative in the subsequent time bin, and it did, $\beta = -4.2$, $SE = 0.97$, $t(0.01) = -4.28$, $p < .001$.

[8] Because stimuli were removed from the screen upon response and replaced with a fixation cross, the length of time during which screen luminance was lower due to the black stimuli on the white background varied from trial to trial. Pupil size is known to decrease with increasing luminance (Winn, Whitaker, Elliott, & Phillips, 1994). Thus, it is possible that trials with a slower RT (e.g., incompatible trials on average) could exhibit a larger pupil size simply due to the lower average luminance of the screen during such trials. In order to examine whether the current results may be explained by differences in luminance across trials, as opposed to variation in task demands/cognitive control, RT was correlated with maximum pupil size across trials collapsing across all other variables. The effect was significant, $r(8652) = .04$, $p = .001$, $R^2 = .002$. However, this likely reflects the extremely large number of observations as the effect size was very weak, explaining less than one half of one percent of the variance in maximum pupil response.

Table 2
Fixed Effects Estimates of Task Condition and Time on Pupil Response

Model	Task condition	Intercept	Slope	Quadratic	Cubic
		Predictor			
1	MC compatible	**135.2 (15.3)**	1.3 (.96)	**−2.8 (.05)**	**−.15 (.003)**
	MC incompatible	**177.0 (16.0)**	−.4 (1.04)	**−3.6 (.01)**	**−.18 (.01)**
	MI compatible	**165.7 (15.4)**	−.3 (1.00)	**−3.6 (.08)**	**−.19 (.01)**
	MI incompatible	**210.0 (15.3)**	**3.8 (.96)**	**−3.7 (.05)**	**−.20 (.003)**
2	MC repeat	**156.0 (14.9)**	1.8 (.96)	**−3.1 (.07)**	**−.17 (.005)**
	MC switch	**139.3 (14.9)**	**2.9 (.93)**	**−2.8 (.05)**	**−.16 (.003)**
	MI repeat	**204.9 (14.9)**	1.3 (.96)	**−4.0 (.07)**	**−.21 (.005)**
	MI switch	**196.2 (14.9)**	**3.4 (.93)**	**−3.5 (.05)**	**−.19 (.003)**
3	MC compatible	**135.2 (15.3)**	1.3 (.96)	**−2.8 (.05)**	**−.15 (.003)**
	MC incompatible	**173.9 (15.4)**	**6.34 (1.00)**	**−3.1 (.08)**	**−.18 (.01)**
	MI compatible	**165.7 (15.4)**	−.3 (1.00)	**−3.6 (.08)**	**−.19 (.01)**
	MI incompatible	**210.0 (15.3)**	**3.8 (.96)**	**−3.7 (.05)**	**−.20 (.003)**

Note. Values outside of parentheses represent betas, those within are standard errors of the betas. Bolded values are significant at the .01 level. *p*-values estimated using Satterthwaite approximation. MC = mostly compatible; MI = mostly incompatible.

should reveal that the lagging curve exhibits a positive slope relative to the other curve (which should exhibit a nonsignificant slope). Model 2 was centered at the peak of the mostly compatible–compatible curve and effect coding was used to compare the slopes between the two mostly compatible curves. While the mostly compatible-incompatible slope was significantly positive, $\beta = 6.3$, $SE = 1.00$, $t(0.02) = 6.31$, $p < .001$, the mostly compatible–compatible slope was nonsignificant, $\beta = 1.3$, $SE = 0.96$, $t(0.01) = 1.35$, $p = .18$, resulting in a significant difference, $M_{\text{difference}} = -4.37$, $SE = 0.96$, $z = -4.54$, $p < .001$. This suggests that the mostly compatible-incompatible pupil response was continuing to increase after the point at which the mostly compatible-compatible pupil response had peaked. As can be seen in Figure 5, in contrast to the mostly compatible curves, the two mostly incompatible curves appear to peak during the same time bin. However, the above analysis could not be applied to the mostly incompatible curves because the results would have been uninterpretable due to the lack of a nonsignificant slope at the mostly incompatible-incompatible peak (see Footnote 7 for further discussion).

Discussion

The current study investigated whether modulation of cognitive effort might be observed in the absence of explicit awareness of task demands for heightened control. If awareness of task demands is required in order to modulate cognitive effort, then a CSPC paradigm that elicits behavioral differences in control outside of awareness of such demands should reveal no systematic differences in cognitive effort. The current results, however, indicate that systematic differences in cognitive effort do occur in a CSPC paradigm. In the location associated with a high frequency of conflict (i.e., the mostly incompatible location), average peak pupil response was larger than in the location associated with a low frequency of conflict (i.e., the mostly compatible location), regardless of trial type and regardless of a switch or repeat in context (i.e., location). This difference in pupil response occurred despite (a) participants' inability to correctly report that locations differed in the frequency of conflicting stimuli, (b) participants' confidence in their proportion estimates suggesting they were merely guessing, and (c) participants not systematically choosing the mostly incompatible location as being more difficult. In sum, these findings suggest that explicit awareness of conflict frequency is not required in order for cognitive effort to be modulated.

The theoretical implications are twofold. One implication is that the findings challenge classic accounts of cognitive control. Classic accounts initially described control as slow, strategic and willful (controlled by conscious intentions), later distinguishing automatic pro-

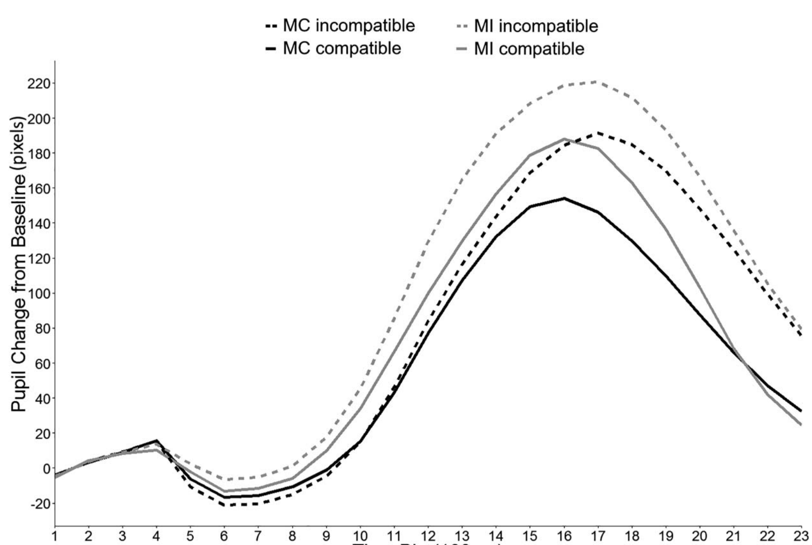

Figure 4. Grand averages representing change in pupil size from baseline as a function of trial type and proportion compatibility. Stimulus onset occurred at the end of the second time bin. MC = mostly compatible; MI = mostly incompatible.

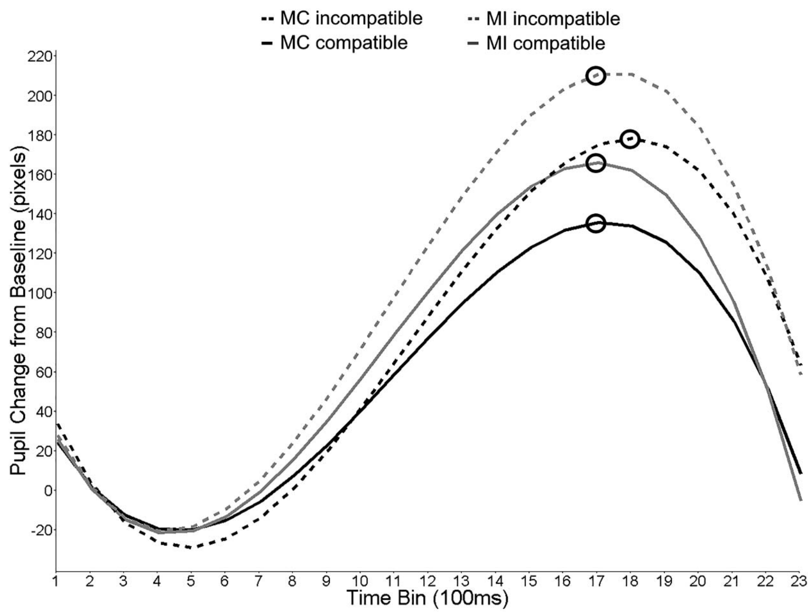

Figure 5. Model estimated values as a function of trial type and proportion compatibility. Peak responses used as centering points for Model 1 are marked with circles. Model 3 changed the centering point of the mostly compatible-incompatible curve from Time Bin 18 to Time Bin 17. No other centering points were changed. MC = mostly compatible; MI = mostly incompatible.

cesses as relatively effortless (e.g., Posner & Snyder, 1975; Shiffrin & Schneider, 1977). The discovery of CSPC and item-specific proportion congruence effects in recent years demonstrated that cognitive control can also act rapidly and flexibly, thereby fostering views of control that included slow and strategic as well as fast and flexible mechanisms (Bugg, 2012; Bugg & Crump, 2012; see proactive/reactive distinction of Braver et al., 2007). Indeed, Jacoby et al. (2003) used the term "automatic control" to describe how the latter type of control mechanism produced an item-specific proportion congruence effect, a term that has at least implicitly been adopted to capture the fast, flexible, and seemingly effortless retrieval of control settings on a location-by-location basis in the CSPC paradigm (Bugg & Crump, 2012). Yet, using pupillometry, the current findings demonstrated for the first time that the CSPC effect is associated with modulations of cognitive effort as a function of location. Critically, this suggests fast and flexible forms of cognitive control may not be wholly automatic in the classic sense—although they appear to be automatic in that they operate outside of awareness of task demands, they also appear to involve modulations of effort just like the slow and strategic forms of control referenced in classic theoretical accounts.

It is clear from the awareness data that the modulations of effort accompanying cognitive control did not occur on the basis of explicit knowledge regarding the proportion compatibility of each location (cf. Blais et al., 2012, for evidence that retrospective reports of awareness may also not drive list-wide proportion congruence effects, which have often been assumed to reflect a slow and strategic mechanism). An intriguing possibility is that the modulations of effort may occur implicitly, at least in the context of the CSPC paradigm. In line with this possibility, CSPC effects have been observed when visual masking is used to prevent awareness of conflict and context cues (Reuss et al., 2014; though see Heinemann, Kunde, & Kiesel, 2009; Schouppe, de Ferrerre, Van Opstal, Braem, & Notebaert, 2014) that, given the present data, presumably guide effortful adjustments. However, an alternative possibility is that retrospective estimates of proportion compatibility are rather limited in gauging participants' awareness of location-specific task demands. One concern is that participants may be aware of these demands but the questions participants are asked may not be sufficiently sensitive to capture this awareness. Future studies may gain traction on this issue by incorporating other, potentially more sensitive correlates of awareness such as subjective effort, perceived performance, and affect for each location context.

Another concern is that the retrospective estimates of proportion compatibility cannot gauge awareness during the moment location-specific task demands are experienced, which is perhaps when participants may be most aware of such demands or the amount of effort they are exerting. To counter this limitation, future studies may need to develop novel, online measures of awareness that can be collected *as* participants respond to stimuli in each location, but that do not contaminate task performance.[9] A primary concern is to choose an approach that minimizes the possibility that repeated attempts to gauge awareness across trials induce or enhance awareness in a way that is not typical of the CSPC paradigm. A step in this direction

[9] We examined whether speed of initial saccades during a trial might serve as an online indicator of awareness, with the rationale being that saccade speed may be indicative of a preference for a particular location (such as the low control location, as in the choice task of Schouppe, Ridderinkhof et al., 2014). However, this did not appear to be the case. Initial saccades were no faster for mostly compatible trials (M = 376 ms, SD = 29) than for mostly incompatible trials (M = 378 ms, SD = 19), $t(31) = -0.44$, $p = .662$, $d = -0.07$, 95% CI [−12.63, 8.14]. This was also true for compatible trials (M = 381 ms, SD = 16) and incompatible trials (M = 380 ms, SD = 16), $t(31) = 1.02$, $p = .316$, $d = 0.13$, 95% CI [−1.31, 3.94].

would be to employ a variant of the choice task used by Schouppe, Ridderinkhof, Verguts, and Notebaert (2014) in conjunction with eye-tracking during a CSPC paradigm. Schouppe, Ridderinkhof et al. (2014) had participants perform a CSPC task in which the contextual cue (a black square or a black diamond) was presented prior to stimulus onset. A CSPC effect was found such that the congruency effect in a Stroop task was smaller for the mostly incongruent shape than the mostly congruent shape. Most critically, Schouppe, Ridderinkhof et al. (2014) gauged awareness of control demands by having participants perform a choice task (in blocks that were interleaved with the CSPC task blocks). In the choice task blocks, participants chose to perform trials associated with the black square (e.g., the mostly congruent context) or trials associated with the black diamond (e.g., the mostly incongruent context). Participants displayed a preference for the mostly congruent (i.e., low conflict frequency) context, which the authors interpreted as indicating participants' preference for low control demands (see also Schouppe, de Ferrerre et al., 2014; cf. Westbrook & Braver, 2015). This finding suggests that the choice task may be an effective alternative approach to gauging awareness of context-dependent conflict frequency (control demands). Interestingly, the choice participants made was uncorrelated with the size of their CSPC effects. This highlights the potential outcome that participants may be aware of, but not always use, information about contextual differences (e.g., control demands) to guide their performance (cf. Maia & McClelland, 2004).

The second theoretical implication pertains to the findings of an effect of proportion compatibility but no interaction between proportion compatibility and trial type on peak pupil response. These patterns suggest that effort was modulated by the location in which a stimulus was presented, irrespective of trial type. Converging evidence for this interpretation is the general slowing in RT found in the mostly incompatible location relative to the mostly compatible location when collapsing across trial types. These findings are consistent with the episodic retrieval account that posits that abstract attentional settings are retrieved upon presentation of a stimulus in a given location—a narrower attentional setting is adopted in the mostly incompatible location whereas a broader attentional setting is adopted in the mostly compatible location (Crump & Milliken, 2009). The current findings indicate that engagement of a narrower attentional setting induces more effort than engagement of a broader attentional setting, and this pattern does not depend on whether the trial comprises a compatible or incompatible stimulus. Importantly, this suggests that it is the location that is serving to cue the relevant attentional setting and not a particular stimulus type within a given location.

The findings from the context switch analysis also provided support for location as the primary cue for the retrieval of control settings. The mostly incompatible location was associated with a larger peak pupil response than the mostly compatible location on both context repeat trials and context switch trials. Had an effect of proportion compatibility been found in the pupil response on context repeat trials but not context switch trials, it would have implied that control settings (and corresponding levels of effort engagement) are merely carried over from the preceding trial (for evidence of carryover reflecting an increase vs. a decrease, respectively, in pupil size following incongruent trials see Wendt et al., 2014 and Van Steenbergen & Band, 2013), with switches interrupting any carryover. Inversely, had an effect of proportion compatibility been found following context switches but not context repeats, this may have implied that a switch in context is what cues the retrieval of a control setting. Instead the findings suggest that location triggers retrieval of the optimal control setting on each trial, regardless of whether the context has switched or repeated, with retrieval of the narrower setting producing a larger pupil response compared with the broader setting. However, additional research is needed to better understand effects of context change because, in another CSPC paradigm, context switches but not context repeats were associated with neural activity corresponding to the retrieval of context appropriate control settings (King, Korb et al., 2012).

The current pattern of findings (effect of the proportion compatibility of a location on peak pupil response but no interaction of proportion compatibility and trial type on peak pupil response) counters the possibility that peak pupil response in the CSPC paradigm is driven by frequency or event learning processes (e.g., an unexpected trial type or the ease of retrieving associated responses). Potentially, the fact that participants were unaware of the differences in proportion compatibility in each location may explain why there was no influence of experiencing an unexpected trial type on pupil response. Compounding this was the 50% global probability of a trial being conflicting, such that no conscious expectancy of conflict was violated on a trial-by-trial basis. If participants explicitly or implicitly expected more or less conflict in a given location (e.g., leading to more or less response caution; King, Donkin et al., 2012), an interaction may have been observed for peak pupil response (e.g., a larger response for the incompatible trial type in the mostly compatible location; cf. Kamp & Donchin, 2015). Despite not observing this, it is worth noting that in prior research computational models based on either response caution or attentional filtering (i.e., an episodically retrieved control mechanism) both explained the CSPC effect relatively well (King, Donkin et al., 2012), with the present results favoring an attentional filtering model. Similarly, had it been the case that peak pupil response was influenced by the learning of responses associated with particular stimuli in a given context, then peak pupil response should have been comparable for compatible and incompatible trials in the mostly incompatible location (with use of a four-choice task, responses on each trial type are equally contingent) but smaller on compatible than incompatible trials in the mostly compatible location, indicating that the need for control (or increased effort) was bypassed on the single, high contingency trial type in our four-choice flanker task (cf. Schmidt & Besner, 2008). However, future studies should include matched sets of unbiased items in the mostly incompatible and mostly compatible locations, as has been done behaviorally (Crump & Milliken, 2009), to more definitively rule out the associative learning account.

The results of the exploratory analyses performed on the time course of the pupil response also appear to provide support for the episodic retrieval account. The attentional setting retrieved for the mostly incompatible location is narrow (i.e., filters the flanking arrows to a greater degree) and a narrow attentional setting should allow for efficient selection of the target regardless of trial type. This converges with the observation that both compatible and incompatible trial types appear to peak during the same time bin in the mostly incompatible location (though for reasons described in Footnote 7, this could not be confirmed statistically). For the mostly compatible location, the retrieved attentional setting is broad (i.e., filters flanking arrows to a lesser degree), thereby allowing the flanking arrows to have a greater influence on performance. As such, the attentional setting that is retrieved in the mostly compatible location affords efficient target selection on compatible trials but is detrimental to performance on incompatible trials. From this perspective, mostly compatible–incompatible trials represent a unique challenge to the cognitive system in that the rapidly retrieved control setting must be flexibly adjusted to avoid slow or errant responding. This may explain why there is a time lag in this condition relative to the mostly compatible–compatible condition in the current study.

Alternative Accounts of Changes in Pupil Response

Changes in pupil diameter have been classically associated with changes in cognitive effort (Kahneman, 1973) and the above interpretations of the current findings ascribe to this view. However, two recent theories offer unique characterizations of changes in pupil response that encourage alternative interpretations of the present results. The first states that pupillary activity is linked to autonomic arousal in the brain, while the second argues that the experience of aversive affect, which may be reflected in changes in pupil diameter, is a critical cue for the signaling of control.

The first, adaptive gain theory, posits that pupillary activity reflects activity in the locus coeruleus-norepinephrine system (Aston-Jones & Cohen, 2005), a system that has long been associated with arousal (Berlucchi, 1997). Phasic pupil responses (such as those recorded in the present study) are considered indicative of task engagement and are strongest during periods of optimal performance, with corresponding norepinephrine release providing boosts in neural gain. According to this theory, the current results may reflect autonomic arousal differences between trial types and locations (e.g., mostly incompatible location associated with higher arousal relative to the mostly compatible location).

Adaptive gain theory meshes well with the second theory that argues control is recruited through the aversive experience of response conflict (Dreisbach & Fischer, 2015; for evidence that conflicting stimuli are aversive, see Fritz & Dreisbach, 2013). That is, conflict produces a subjective experience that is aversive, and thereby triggers adjustments in control that serve to counter the negative affect (see Dreisbach & Fischer, 2011, for important evidence showing that conflict-free, disfluent stimuli are also aversive and trigger such control adjustments; cf. Desender, Van Opstal, & Van den Bussche, 2014, who found that the subjective experience of conflict drives control adjustments underlying the congruency sequence effect). This is pertinent to the present findings because pupillometry appears to be well suited to detecting changes in affective experience (see Chiesa, Liuzza, Acciarino, & Aglioti, 2015 for evidence that pupillometry is even sensitive to subliminally presented affect primes). For instance, it has been shown that pupil diameter increases more in response to negative stimuli compared with neutral stimuli (Snowden et al., 2016). In addition, pupil diameter has been shown to be larger following incorrect than correct responses during a flanker task, with the largest diameter following errors occurring on congruent stimuli, the least frequently committed error (Braem, Coenen, Bombeke, Van Bochove, & Notebaert, 2015). Braem and colleagues interpreted this as indicating that the affective experience of "cognitive surprise" may lead to control adjustments (Braem et al., 2015). Accordingly, the changes in pupil diameter observed in the present study might be a potential indicator of the aversive signal used to recruit control. In particular, the larger pupil diameter that was observed in response to incongruent stimuli and to the mostly incompatible location may reflect that these conditions are associated with a more aversive subjective experience (more negative affect) than congruent stimuli or the mostly compatible location. Interestingly, participants in the current study did not systematically choose the mostly incompatible location as being more difficult, which may be a potential proxy for subjective negative affect. More sensitive measures of participants' location-specific affective experiences are therefore needed to draw firmer conclusions.

Conclusion

Using pupillometry in the context of a CSPC paradigm, it was demonstrated that cognitive effort is modulated outside the explicit awareness of conflict frequency (context-specific task demands). More effort was engaged in the mostly incompatible location, where a narrow attentional setting is retrieved, than in the mostly compatible location where a broad attentional setting is retrieved. Behaviorally, the heightened effort in the mostly incompatible location was accompanied by overall slower RTs and a reduced compatibility effect. These patterns call to mind Kahneman's (1973) analogy of mental effort to load on an electrical grid: When a load on the grid is incurred, the generator's governor causes more fuel to be burned in order to flexibly meet changing demands on the grid. As the power grid lacks the need for an aware operator to modulate power in the face of rapidly changing load demands, so too, it appears, does the modulation of effort in meeting task demands within the flanker paradigm. The current findings demonstrate that cognitive control may operate fast, flexibly, and outside of awareness, but not effortlessly (i.e., not wholly automatically; Jacoby et al., 2003), and therefore advocate for the continued refinement of definitions and accounts of cognitive control.

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