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Blocking Visual Awareness with Continuous Flash Suppression Prevents Cognitive Control

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BLOCKING VISUAL AWARENESS WITH CONTINUOUS FLASH SUPPRESSION
PREVENTS COGNITIVE CONTROL

by

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ABSTRACT

Blocking Visual Awareness with Continuous Flash Suppression
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Cognitive control refers to a set of functions that allow for the execution of goal-directed behavior while remaining flexible to changes in task demands. Findings addressing whether or not awareness is necessary to elicit cognitive control are inconsistent, possibly stemming from the short stimulus presentation times employed in most masking paradigms, which could prevent sufficient processing time in some cases or provide a gist of the masked stimulus in other cases. The present study examined the necessity of awareness in cognitive control using Continuous Flash Suppression (CFS) to suppress stimulus awareness for periods of time longer than possible with other masking paradigms. Cognitive control was evoked using flanker arrow tasks in two experiments, wherein participants were asked to respond to a target arrow during congruent, incongruent, and no-flanker conditions. In the first experiment, one eye was presented with the flanker arrows while the opposite eye was presented with the target arrow alone (unmasked condition) or with CFS (masked condition). In the second experiment, CFS was presented in the same eye as the target arrow on every trial but the flanker arrows were displayed in either the same eye (unmasked condition) or opposite eye (masked condition) as the CFS and target arrow. Both experiments showed significantly slowed response times (RTs) for incongruent flankers relative to congruent flankers during unmasked trials, indicating a conflict effect. However, in masked trials, RTs were not significantly different between congruent and incongruent flanker conditions. These results suggest that cognitive control is not recruited when awareness of conflicting information is suppressed.

ACKNOWLEDGMENTS

The work in the present thesis has been presented in multiple forms since its initial conception when I was a student of the Behavioral and Cognitive Neuroscience (BCN) PhD program at CUNY. It was initially presented as a poster for the Society for Neuroscience's 2013 meeting (Neuroscience 2013: Awareness is necessary for cognitive control. J. T. Lo Voi; Q. Wu; Y. Wu; J. Fan. CUNY Grad. Ctr., Peking Univ., Queens Col., Mount Sinai Sch. of Med.). It later became the basis for my first doctoral exam in January 2014, with Drs. Jin Fan, Tony Ro, and Elizabeth Chua serving as committee members. After my withdrawal from the BCN program, the work would eventually be published in the journal Frontiers in Psychology, though by this time I had ceded first authorship to my former lab-mate Qiong Wu and was credited as "co-first author" (Wu Q, Lo Voi JTH, Lee TY, Mackie M-A, Wu Y and Fan J (2015). Interocular suppression prevents interference in a flanker task. *Front. Psychol*. 6:1110. doi: 10.3389/fpsyg.2015.01110).

Where reasonable, I have changed text and figures in the present thesis to more closely reflect the paper in its initial form when presented as my first doctoral exam, the writing of which was entirely my own. However, as the body of the final published work is largely my writing and I contributed to the edits after peer-review, much of the content of this thesis will remain similar to the final published work. I retain joint copyright ownership of the text and figures in the final publication, along with the co-authors who are listed above (Frontiers' copyright guidelines can be read at https://www.frontiersin.org/journals/psychology#author-guidelines).

I am indebted to all of my former lab-mates and to Dr. Jin Fan, and so I would like to credit those who were instrumental in allowing this work to take its final shape. Listed below are the author contributions, acknowledgements, and disclaimers as seen in the final published work:

“Qiong Wu and Jonathan Lo Voi contributed equally to experimental design, data collection, and drafting of the work. Thomas Lee contributed to data analysis, interpretation of data, and drafting of the work. Melissa-Ann Mackie contributed to the interpretation of data and drafting of the work. Yanhong Wu contributed to the interpretation of data and drafting of the work. Jin Fan was involved in all of these aspects. All authors approved the final version to be published and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

“We thank Dr.Julien Dubois from Christof Koch’s lab for providing MATLAB code to generate the Mondrian images for the CFS mask, and Drs. Elizabeth Chua and Tony Ro for their helpful comments and suggestions. Research reported in this publication was supported by the National Institute of Mental Health of the National Institutes of Health under Award Number R01 MH094305 to Jin Fan. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. Yanhong Wu was supported by the Ministry of Science and Technology of China (2015CB351800).”

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CHAPTER 1: INTRODUCTION

Cognitive control refers to those functions that mediate purposeful, goal-directed behavior while allowing for the flexibility to alter behavior with changing task demands (Fan, et al., 2009; Mackie, Van Dam, & Fan, 2013; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). Cognitive control has been studied by manipulating stimuli and response conflict, as in various versions of Stroop tasks (Stroop, 1935), Eriksen flanker tasks (Eriksen and Eriksen, 1974), and Simon tasks (Simon and Berbaum, 1990). In these experiments, cognitive control is elicited by the presence of conflict between "congruent" stimuli and "incongruent" stimuli, the latter of which are usually accompanied by increased response times (RTs) and decreased accuracy. This difference in behavior between incongruent and congruent stimuli is defined as the "conflict effect" and is interpreted as an indication of increased cognitive control over attentional resources (Botvinick et al., 2001; Fan et al., 2003, 2007, 2008).

Research in cognitive neuroscience has made it apparent that the brain is capable of higher-level processing of some information that never reaches awareness. A wide range of cognitive abilities have been demonstrated without awareness, including reading and arithmetic (Sklar et al., 2012; but see Kang, Blake, & Woodman, 2011), monetary value assessment (Pessiglione, et al., 2007), and inhibitory control (van Gaal, Ridderinkhof, van den Wildenberg, & Lamme, 2009). It is possible that processing information outside of awareness may be possible due to inputs from early, subcortical visual pathways (Hall, West, & Szatmari, 2007; Morris, Ohman, & Dolan, 1999; Pasley, Mayes, & Schultz, 2004; Troiani & Schultz, 2013). Though the full extent of information processing outside of awareness is largely unknown, the ability of the brain to perform higher cognitive tasks in the absence of awareness highlights the gaps in our knowledge regarding the function of conscious awareness.

It has previously been suggested that cognitive control is impossible without awareness (Dehaene & Naccache, 2001; Jack & Shallice, 2001). However, recent experiments implementing masking paradigms have challenged the view that awareness is necessary for cognitive control, by demonstrating cognitive control in subjects presented with masked stimuli. Results from these experiments have demonstrated unconscious activation of task sets using masked cues (Reuss, Kiesel, Kunde, & Hommel, 2011); unconscious interference from Stroop tasks (Klapp, 2007); and unconscious context effects on behavioral responses (Van Opstal, Calderon, Gevers, & Verguts, 2011). Further, neuroimaging studies provide evidence for unconscious activation of brain regions, such as the anterior cingulate cortex (Ursu, Clark, Aizenstein, Stenger, & Carter, 2009) and prefrontal cortex (Lau & Passingham, 2007; van Gaal, Ridderinkhof, Scholte, & Lamme, 2010), that are involved in cognitive control. However, other experiments have found that behavioral effects associated with cognitive control are not seen when stimuli do not reach awareness (Ansorge, Fuchs, Khalid, & Kunde, 2011; Boy, Husain, & Sumner, 2010; Frings & Wentura, 2008; Heinemann, Kunde, & Kiesel, 2009; Van den Bussche, Segers, & Reynvoet, 2008).

Though the discrepancies in the above findings may simply stem from the type of information being processed in each experiment (Boy, et al., 2010; Kunde, Reuss, & Kiesel, 2012; van Gaal & Lamme, 2012), it may also be an effect of the type of masking paradigm used. Many masking experiments employ briefly-presented stimuli that are quickly replaced with a mask, as is seen with backward-masking paradigms (Ansorge, et al., 2011; Rahnev, Huang, & Lau, 2012; Weibel, Giersch, Dehaene, & Huron, 2013). Though experiments utilizing briefly-presented stimuli have demonstrated the effects of cognitive control during unmasked trials, cognitive control is not always elicited during masked trials (Ansorge, et al., 2011; Frings & Wentura, 2008; Heinemann, et al., 2009). These observations have led to the conclusion that awareness of stimuli is necessary to elicit cognitive control. However, it is important to consider the type of mask used. Paradigms that present a mask immediately after a briefly-presented stimulus may suppress awareness by re-focusing attention onto the mask (Naccache, Blandin, & Dehaene, 2002; Van den Bussche, Hughes, Van Humbeeck, & Reynvoet, 2010; Visser, Bischof, & Di Lollo, 2004). If the masks in these paradigms cause attention to be re-focused, then there may be insufficient time to act upon the previously-presented stimulus. Because cognitive control depends on attention (Fan, et al., 2009; Mackie, et al., 2013; Wang, Liu, & Fan, 2011), the results from these masking experiments may only demonstrate the necessity of attention in eliciting cognitive control, rather than the necessity of awareness (though this assumes that attention and awareness are dissociable; see Cohen, Cavanagh, Chun, & Nakayama, 2012, and Koch & Tsuchiya, 2012). Thus, the experiments leave open the possibility that cognitive control can be elicited without awareness.

The present two experiments aimed to better assess the relationship between cognitive control and awareness. It was hypothesized that cognitive control is a higher-level, "top-down" process that can only operate on information that has reached awareness. Cognitive control was measured in terms of conflict effects on behavioral responses during a flanker-arrow task. Awareness was manipulated using interocular suppression, specifically using continuous flash suppression (CFS). CFS is a powerful masking tool in which a dynamic image composed of flashing multi-colored "Mondrian" patterns is presented to one eye, which prevents awareness of a stable image presented to the opposite eye (Fang and He, 2005; Tsuchiya and Koch, 2005). Because CFS allows for suppression of awareness for longer periods of time compared to other masking paradigms (over seconds, rather than milliseconds; Shimaoka and Kaneko, 2011; Stein and Sterzer, 2011), it is ideal for investigating the role of awareness in higher-order cognitive tasks that likely require longer processing times (Peremen and Lamy, 2014; Yang et al., 2014). Thus, if the present experiments fail to demonstrate conflict effects during masked trials of a flanker task, then support is given to the idea that awareness of stimuli is necessary to elicit cognitive control.

CHAPTER 2: GENERAL MATERIALS AND METHODS

Participants

Forty-two individuals (19 females, mean age in years ± SD, 21.74 ± 4.96) participated in Experiment 1 and forty individuals (28 females, mean age in years ± SD, 21.31 ± 5.33) participated in Experiment 2. In Experiment 1, 11 participants were excluded because of errors of omission and 7 participants were excluded because of unsuccessful CFS masking (final N = 24, 11 females, mean age in years ± SD, 21.38 ± 4.53). In Experiment 2, 10 participants were excluded because of errors of omission and 5 participants were excluded because of unsuccessful CFS masking (final N = 25, 16 females, mean age in years ± SD, 21.5 ± 5.78). Participants were recruited from the Psychology 101 subject pool at Queens College and were granted class credits for their participation. All participants had normal or corrected-to-normal vision. The experiment was approved by the Institutional Review Board of Queens College of the City University of New York. All participants signed informed consent forms prior to the start of the experimental procedure.

Apparatus

A stereoscopic shutter goggle system (ELSA wired 3D goggles with attached head-strap) was used to display the stimuli and mask. The goggle system allowed independent presentation of stimuli to each eye and eliminated the need for a head and chin rest, as is seen with stereoscopic mirror setups that are commonly used in CSF experiments (Carmel, Arcaro, Kastner, & Hasson, 2010). The screen resolution for each eye was 800 x 600 pixels.

The experiment was presented using MATLAB R2010b software with Psychophysics Toolbox Version-3 (Brainard, 1997) installed on a Mac Pro 5.1 computer running OSX 10.7. The stimuli were sent to the goggles using a stereo-mode defined in the functions included with the Psychophysics Toolbox. Each goggle eyepiece received alternating frames, with one eye receiving even frames and the other receiving odd frames (total refresh rate of 30 Hz for each eyepiece). Viewing distance to each eyepiece was approximately 2.5 cm.

Stimuli

The experiment used a variation of the Eriksen flanker task (Eriksen & Eriksen, 1974) with arrows serving as targets and flankers (each approximately 2.8° of visual angle). The stimuli are illustrated in Figure 1. A central fixation cross of 16 x 16 pixels was presented to both eyes for the duration of the experiment. Participants viewed a central target arrow pointing either to the left or right, which on some trials could be presented simultaneously with four flanker arrows. The arrows (RGB values = 103) were presented at a darker contrast than the gray background (RGB values = 128). The arrow head was approximately 3.3 times larger than the arrow base to allow for quick discrimination of direction. The target arrow's location always overlapped with the location of the fixation cross. Depending on the trial, the target and flanker arrows could appear in either the same eye or in different eyes. To facilitate the fusing of the images presented to each eye, a square border of alternating black and white bands was presented to both eyes throughout the experiment.

CFS was used to mask the flanker arrows in each version of the experiment. The Mondrian images comprising the CFS mask were a set of multicolored overlapping ovals that filled the space inside the square border and were cycled at a rate of 10 Hz (modeled after the CFS mask in Tsuchiya and Koch, 2005). Ovals were used due to concerns that the presence of sharp angles could interfere with discriminating the sharp angles of the target arrow. CSF was used because it allowed a longer duration of masking time, ensuring that any potential lack of flanker conflict could not be explained away by an insufficient amount of time to process the conflicting information.

Data analysis

Participants were excluded from further analysis if they made omission errors for more than

20% of trials in any run. Participants were also excluded if they performed above chance and reported "yes" during a fifth run that was included to determine if participants were aware of the flanker arrows, despite the presence of the CSF mask.

Mean RTs and accuracy were calculated for each trial type. Trials with incorrect responses were excluded from the analysis of RTs. For both RT and accuracy, we conducted a two-way within-subjects ANOVA with flanker condition (no flankers, congruent flankers, incongruent flankers) and presence of CFS mask (CFS mask vs no CFS mask) as within-subjects factors. For factors and interactions where assumption of sphericity is violated, a Greenhouse-Geisser correction will be used and adjusted degrees of freedom and p values will be reported. Significance level was set at an α of 0.05, and effect size is calculated as η_p^2.

FIGURE 1

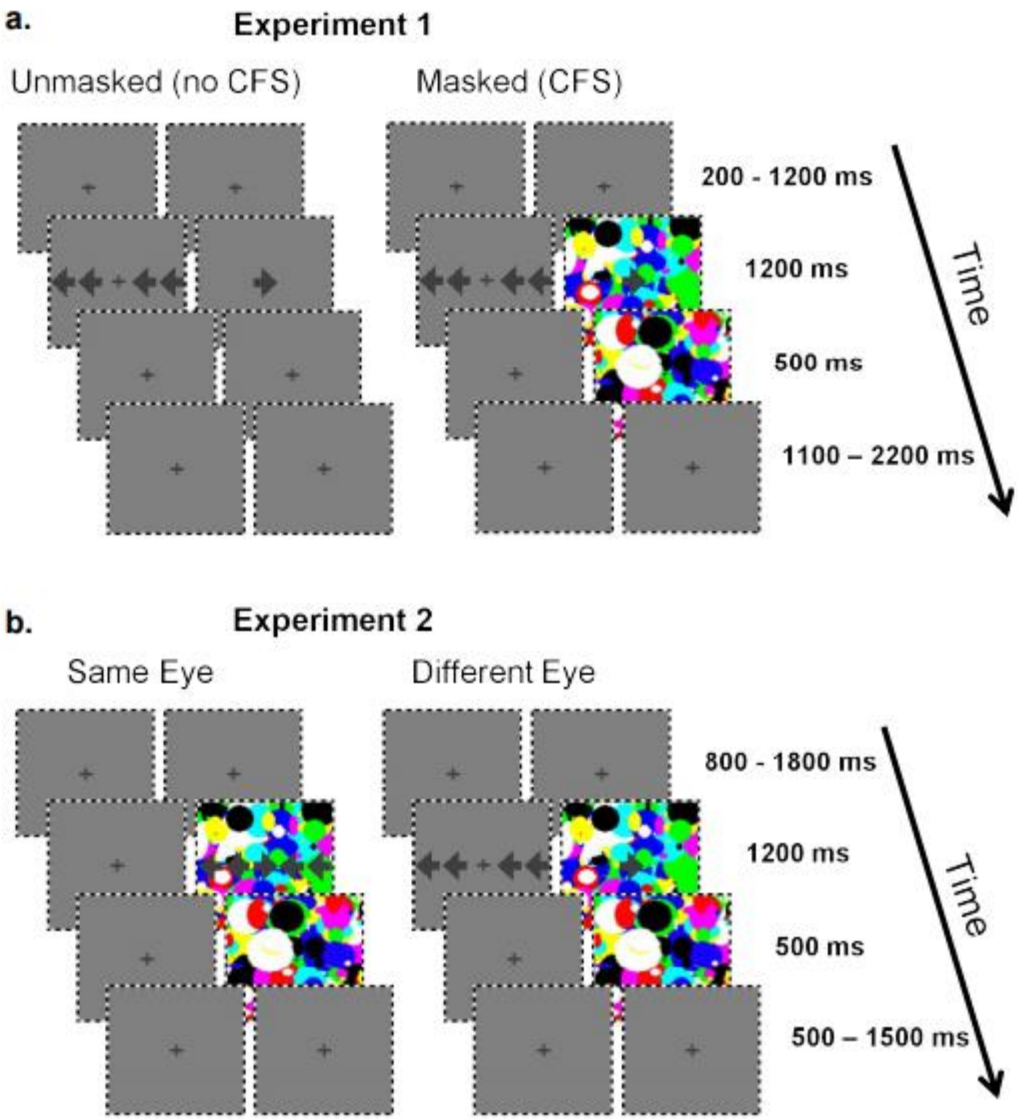

***Figure 1*. The sequence of stimuli in each trial from Experiment 1 (a) and Experiment 2 (b).** In each experiment, a fixation cross was shown to both eyes. One eye was then presented with a central target arrow that appeared in the same location as the fixation cross, while one of three flanker conditions were presented: no flankers, congruent flankers (same direction as target), or incongruent flankers (opposite direction of target). (a) Flanker arrows were presented to the eye opposite the target arrow. Mondrians (CFS) were presented to the same eye as the target arrow only during masked trials.

(b) Mondrians were presented to the same eye as the target arrow during each trial. During unmasked trials, the flankers were presented to the same eye as the target arrow and Mondrians. During masked trials, the flanker arrows appeared in the eye opposite the target arrow and Mondrians. After the presentation of the target arrow in each experiment, Mondrians were presented alone to prevent negative afterimages of the flanker arrows.

CHAPTER 3: EXPERIMENT 1

Task Design

The aim of this experiment was to test for evidence of cognitive control acting upon conflicting information that is presented outside of awareness.

Figure 1a illustrates the stimuli in an example trial. The flanker arrows were presented to the eye opposite the dynamic Mondrian images. Because the target arrow was not meant to be masked by CFS, it was presented to the same eye as the Mondrian images, and was discernable among the Mondrian images. In unmasked trials (no Mondrian images present), flanker arrows were presented to the eye opposite the target arrow for consistency, which additionally ensured that a flanker conflict effect still would be seen even when flankers were presented to the opposite eye from the target. Because the flanker arrows would not be visible during masked trials, trials without flanker arrows were used as a control instead of trials with neutral flankers (e.g. bars without arrow-heads) for both masked and unmasked trials. For unmasked trials (no CFS), it was predicted that a conflict effect (increased RTs and decreased accuracy) would be seen for incongruent flankers relative to congruent flankers or no flankers. For masked trials (CFS present), it was predicted that there would be no conflict effect when comparing all three flanker conditions.

Procedure

Prior to the start of the experiment, participants were instructed to watch the fixation cross at all times. They were told only to indicate the direction of the central target arrow that overlapped with the location of the fixation cross as quickly and accurately as possible, and to ignore any other arrows or colorful images presented. The goggle head-strap was adjusted for each participant’s head and the lights were dimmed to allow optimal viewing. Responses were collected using the left and right arrow keys of a standard keyboard.

The experiment was divided into four runs of the experimental task, with 96 trials per run. Each trial lasted for 4 seconds, for a total of 384 seconds (6.4 minutes) per run. Participants were given the option of taking a break after each run. The experiment was divided into masked and unmasked conditions, each of which were further subdivided into no-flanker, congruent flanker, and incongruent flanker conditions, totaling 6 conditions. Each condition was presented an equal number of times, and the order was randomized within each run. A 30-second fixation period was present at the start and end of each run. At the start of each trial, a fixation cross was presented in isolation for a jittered duration ranging from 200 - 1200 ms. Then the flanker arrows and target arrow appeared, along with the CFS mask in masked trials, for 1200 ms. This was followed by 500 ms of the CFS mask and the fixation cross (no arrows) during masked trials, or the fixation cross alone during unmasked trials. The trial would conclude with the fixation cross presented for a jittered duration of 1100 – 2200 ms, for a total trial time of 4000 ms (Figure 1a). During trials with the CFS mask, the mask and target were presented to one eye, while the flankers or fixation alone were presented to the opposite eye. Trials were counterbalanced such that there was an equal probability of the target appearing in either eye. The presentation of the mask for 500 ms after the target presentation was used to ensure the flanker arrows did not leave a negative afterimage that could influence responses, as was reported in pilot sessions. Responses could be recorded at any time during the target presentation or the 500 ms following the target presentation.

Fifth Run. A fifth run was included to assess whether participants were aware of the flanker arrows, despite the CFS mask. The stimuli in this fifth run were identical to those in the other four runs of the experiment, with the addition of two questions after every trial. Participants were instructed to ignore the target arrow for the fifth run, and to instead watch for the flanker arrows and respond to the two question prompts. The first question asked whether the flanker arrows pointed to the left or the right. This question was presented after all trials, including trials where the flankers were masked and trials where no flankers were present. Participants were told to choose whichever direction “felt right” if no flankers were seen. The second question, presented immediately after the first question, asked whether or not participants saw any flanker arrows. Participants were told to respond “yes” even if they vaguely saw flanker arrows or if they thought they may have caught a glimpse of the flankers but were unsure. This instruction was given to decrease the variability of report criteria among participants (Merikle, 1984). The instruction was added under the assumption that participants’ ability to recognize that something was presented falls under the category of subjective awareness, even if they could not objectively identify what was presented (Sekar, Findley, Poeppel, & Llinas, 2013). The purpose of using both objective and subjective measures to assess flanker visibility was twofold: to have two reference points for defining awareness of the flankers and to look for effects similar to “blindsight” patients, where individuals subjectively report an inability to see stimuli but nevertheless show objective behavioral effects of the stimuli (Hesselmann, Hebart, & Malach, 2011; Marcel, 1998; Poppel, Held, & Frost, 1973).

Results

No blindsight effects (i.e. correct forced-choice responses to flanker arrow direction despite subjective reports that the flanker arrows were unseen) were found for the fifth run; participants performed above chance on forced-choice flanker discrimination only on trials where they indicated having subjectively seen the flankers.

Reaction Times. Figure 2a illustrates the mean RTs and standard errors (SEs) for each trial type. Mauchly’s test indicated that the assumption of sphericity was satisfied for congruency and the interaction between congruency and the CFS mask. Significant main effects were found for both CFS

(F (1, 23) = 26.95, $p < .001$, $\eta_p^2 = .54$) and flanker congruency (F (2, 46) = 41.53, $p < .001$, $\eta_p^2 = .64$). A significant interaction was found between congruency and CFS (F (2, 46) = 39.64, $p < .001$, $\eta_p^2 = .63$), indicating the strength of the flanker conflict effect differed as a function of CFS presence. Planned simple contrasts were performed to investigate the interaction effect. There were significant interactions between unmasked and masked conditions when comparing the no-flanker and incongruent trials, F (1, 23) = 57.36, $p < .001$, $\eta_p^2 = .71$, and the congruent and incongruent trials, F (1, 23) = 56.58, $p < .001$, $\eta_p^2 = .71$. The RT difference between incongruent trials and no-flanker trials (and similarly between congruent and incongruent trials) was significantly greater during unmasked trials than masked trials.

Analyses of simple main effects were carried out to investigate the differences between flanker congruency conditions when split into masked (CFS) and unmasked (no CFS) conditions. The results reveal significantly increased RTs for unmasked congruent trials relative to unmasked no-flanker trials, t (23) = 3.20, $p = .004$; significantly increased RTs for unmasked incongruent trials relative to unmasked no-flanker trials, t (23) = 8.32, $p < .001$; and significantly increased RTs for unmasked incongruent trials relative to unmasked congruent trials t (23) = 7.62, $p < .001$. No significant differences were found when comparing masked congruent and masked no-flanker trials, t (23) = 1.37, $p = .185$, masked incongruent and masked no-flanker trials, t (23) = 1.68, $p = .106$, or masked incongruent trials and masked congruent trials, t (23) = -.11, $p = .911$. RTs were not significantly different when comparing unmasked no-flanker trials to masked no-flanker trials, t (23) = 1.67, $p = .108$. RTs were significantly increased for unmasked congruent trials as compared to masked congruent, t (23) = 3.02, $p = .006$, and for unmasked incongruent trials as compared to masked incongruent trials, t (23) = 7.26, $p < .001$. These results suggest that RTs were not significantly different across flanker trials for the masked condition and RTs increased only during the unmasked condition.

Accuracy

Figure 2b illustrates the mean accuracy and SEs for each trial type. The assumption of sphericity was violated for flanker congruency ($p < .001$) and the interaction between congruency and CFS ($p < .001$), and therefore a Greenhouse-Geisser correction was used. Significant main effects were found for both CFS, F (1, 23) = 6.80, p = .016, η_p^2 = .23, and congruency, F (1.30, 28.90) = 6.46, p = .011, η_p^2 = .22. A significant interaction was found between congruency and CFS, F (1.25, 28.82) = 8.04, p = .005, η_p^2 = .84. Planned simple contrasts were performed to investigate the interaction. There were significant interactions between the unmasked and masked conditions when comparing incongruent and no-flanker trials, F (1, 23) = 9.94, p = .004, η_p^2 = .86, and incongruent and congruent trials, F (1, 23) = 7.59, p = .011, η_p^2 = .75. The interactions indicated that the extent to which accuracy was lower during incongruent trials as compared to either no-flanker trials was significantly greater for unmasked trials than masked trials, and the extent to which accuracy was lower during incongruent trials as compared to congruent trials was significantly greater for unmasked trials than masked trials.

To investigate the differences between congruency conditions when split into masked and unmasked conditions, analyses of simple main effects were conducted. The results revealed significantly lower accuracy for unmasked incongruent trials relative to unmasked no-flanker trials, t (23) = -2.98, p = .007, and significantly lower accuracy for unmasked incongruent trials relative to unmasked congruent trials, t (23) = -2.83, p = .009. No significant difference was found between unmasked no-flanker trials and unmasked congruent trials, t (23) = .89, p = .381. No significant difference in accuracy was found when comparing masked no-flanker trials and masked congruent trials, t (23) < .01, p > .999, masked no-flanker trials and masked incongruent trials, t (23) = -.56, p = .582, or masked congruent trials and masked incongruent trials, t (23) = -.43, p = .670. No significant difference in accuracy was found between unmasked no-flanker trials and masked no-flanker trials, t (23) = .56, p = .582, or unmasked congruent trials and masked congruent trials, t (23) = -.36, p = .724;

but accuracy was lowered significantly for unmasked incongruent trials compared to masked incongruent trials, t (23) = -2.92, p = .008. These results suggest that accuracy dropped only during incongruent trials in the unmasked condition.

Discussion

These RT and accuracy results demonstrate that flanker arrows elicit a conflict effect only in trials without the CFS mask. The typical pattern of incongruent flanker effects appeared only during unmasked trials, suggesting that conflict is only seen when there is awareness of the flanker arrows.

The results also demonstrate that a conflict effect can be elicited even when the target and flanker arrows are presented to different eyes, which was essential for testing the hypothesis. It is worth noting that unmasked congruent flankers led to significantly increased RTs compared to masked congruent flankers. This is likely because even congruent flankers served as a distraction when they were visible, relative to when they were not visible.

FIGURE 2

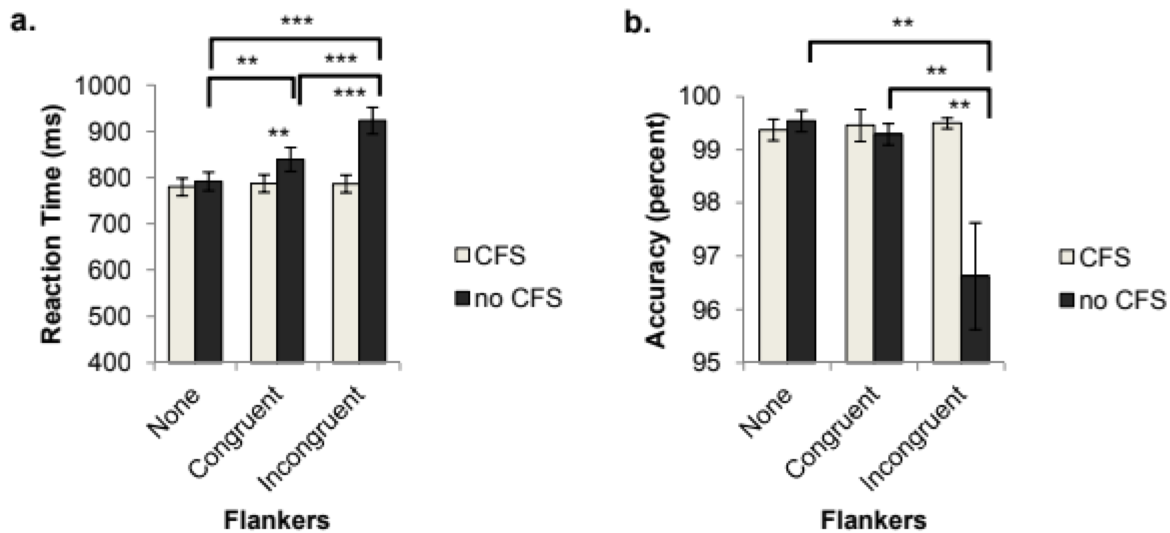

Figure 2. **Behavioral data from Experiment 1.** (a) Reaction time (RT) and (b) accuracy are illustrated for Experiment 1. (a) Incongruent trials without CFS (unmasked condition) led to increased RTs than no-flanker trials without CFS, congruent trials without CFS, and incongruent trials with CFS. Additionally, congruent trials without CFS led to increased RTs than no-flanker trials without CFS and congruent trials with CFS (b) Incongruent trials without CFS led to lower accuracy than no-flanker trials without CFS, congruent trials without CFS, and incongruent trials with CFS.

* significant at $\alpha = .05$; ** significant at $\alpha = .01$; *** significant at $\alpha = .001$

CHAPTER 4: EXPERIMENT 2

Task Design

Though Experiment 1 would allow for the quantification of a flanker conflict effect when the flankers were presented to the eye opposite the target arrow, it would not address the possibility that differences in responses could be due to the Mondrian images themselves, since CFS was not present on unmasked trials. As such, if no conflict effect was seen for masked trials in Experiment 1, it would be unclear if this was due to successful masking of the flankers; or, instead, if some property of the Mondrian images makes it easier to ignore information around the target. Indeed, a high perceptual load can aid in the suppression of irrelevant distractor information (Lavie, Hirst, de Fockert, & Viding, 2004). As a result, it is possible that no conflict effect would be seen in Experiment 1 during trials with CFS, even if flankers outside of awareness could theoretically elicit a conflict effect. Experiment 2 better controls for this possibility by presenting the Mondrians on each trial while manipulating whether the flankers appear in the same eye (unmasked) or opposite eye (masked) as the Mondrians (Watanabe, et al., 2011; Yuval-Greenberg & Heeger, 2013).

The experimental stimuli, including CFS mask, arrows, fixation cross, and frame, were all identical to Experiment 1, with the exception that the flanker arrows appeared in the same eye as the target arrow and Mondrians on half of the trials. This ensured that the flanker arrows would be visible on such trials, despite the Mondrians always being present. We predicted that RTs would increase and accuracy would decrease for incongruent trials, but this conflict effect would only be seen when the flanker arrows appeared in the same eye as the Mondrians and target arrow (unmasked trials).

Procedure

The experimental procedure was nearly identical to Experiment 1, with the following differences. Instead of masked and unmasked trials two flanker-eye conditions were presented. In the *same-eye* condition, the flanker arrows appeared in the same eye as the Mondrians and target arrow. In the *different-eye* condition, the flanker arrows appeared in the eye opposite the Mondrians and target arrow. This condition was equivalent to the masked trials of Experiment 1. This manipulation resulted in 2 flanker-eye (same-eye vs. different eye) x 3 flanker type (no flanker, congruent flanker, and incongruent flanker) conditions.

At the onset of each trial, the fixation cross duration was jittered for 800 – 1800 ms, followed by presentation of the Mondrians with the target (and flankers when applicable) for 1200 ms. The Mondrians and fixation cross were then presented for 500 ms, and the trial concluded with the fixation cross duration jittered for 500 – 1500 ms, for a total trial time of 4000 ms (Figure 1b). It is worth pointing out that the no-flanker trials in both the same-eye and different-eye conditions were identical, and so one-third of all trials presented only the target arrow and CFS mask to one eye. In all other respects Experiment 2 was identical to Experiment 1.

Results

Similar to Experiment 1, no blindsight effects were found for the fifth run. Participants again performed above chance on forced-choice flanker discrimination only on trials where they indicated having subjectively seen the flankers.

Reaction Times. Figure 3a illustrates the mean RTs and SEs for each trial type. The assumption of sphericity was satisfied for both congruency and the interaction between congruency and the flanker-eye conditions. Significant main effects were found for flanker-eye, F (1, 23) = 63.26, p <.001, η_p^2 = .73, and for congruency, F (2, 46) = 46.74, p < .001, η_p^2 = .67. A significant interaction was found between congruency and flanker-eye, F (2, 46) = 64.35, p < .001, η_p^2 = .74, indicating the strength of the flanker conflict effect differed as a function of flanker-eye. Planned simple contrasts were performed to investigate the interaction. There were significant interactions between the same-eye (unmasked) and different-eye (masked) conditions when comparing incongruent and no-flanker trials, F (1, 23) = 82.57, $p < .001$, $\eta_p^2 = .78$, and incongruent and congruent trials, F (1, 23) = 85.05, $p < .001$, $\eta_p^2 = .79$. The interactions indicated that the extent to which RTs were greater during incongruent trials relative to no-flanker trials was significantly greater during the same-eye condition than the different-eye condition, and the extent to RTs were greater during incongruent trials relative to congruent trials was significantly greater during the same-eye condition than the different-eye condition.

Analyses of simple main effects were conducted to investigate the differences between congruency conditions when split into the same-eye (unmasked) and different-eye (masked) conditions. The results revealed significantly increased RTs for same-eye incongruent trials relative to same-eye no-flanker trials the, t (23) = 9.46, $p < .001$, and for same-eye incongruent trials relative to same-eye congruent trials, t (23) = 10.27, $p < .001$; but no significant difference was found between same-eye congruent trials and same-eye no-flanker trials, t (23) = 2.00, $p = .057$. No significant differences in RTs were found when comparing different-eye congruent trials and different-eye no-flanker trials, t (23) = .66, $p = .515$, different-eye incongruent trials and different-eye no-flanker trials, t (23) = .25, $p = .804$, or different-eye incongruent trials and different-eye congruent trials, t (23) = -.40, $p = .691$. RTs were significantly increased for same-eye congruent trials compared to different-eye congruent trials, t (23) = 2.88, $p = .008$, and for same-eye incongruent trials as compared to different-eye incongruent trials, t (23) = 10.13, $p < .001$; but no significant difference was found between same-eye no-flanker trials and different-eye no-flanker trials, t (23) = 1.55, $p = .134$. These results suggest that RTs were not significantly different across the three flanker trials for the different-eye condition and slowed down only during incongruent trials in the same-eye condition.

Accuracy

Figure 3b illustrates the mean accuracy and SEs for each trial type. The assumption of sphericity was not satisfied for flanker congruency (*p* = .029), and therefore a Greenhouse-Geisser correction was used. Significant main effects were found for flanker-eye, *F* (1, 23) = 5.47, *p* = .028, and flanker congruency, *F* (1.57, 36.10) = 6.03, *p* = .009. The assumption of sphericity was satisfied for the interaction between congruency and flanker-eye. A significant interaction was found between congruency and flanker-eye, *F* (2, 46) = 7.16, *p* = .002, η_p^2 = .92. Planned simple contrasts were performed to investigate the interaction. There were significant interactions between the same-eye (unmasked) and different-eye (masked) conditions when comparing incongruent and no-flanker trials, *F* (1, 23) = 9.80, *p* = .005, η_p^2 = .85, and incongruent and congruent trials, *F* (1, 23) = 9.32, *p* = .006, η_p^2 = .83. The interactions indicated that the extent to which accuracy was lower during incongruent trials as compared to no-flanker trials was significantly greater for the same-eye condition than the different-eye condition, and the extent to which accuracy was lower for incongruent trials compared to congruent trials was significantly greater for same-eye condition than for the different-eye condition. Analyses of simple main effects were conducted to investigate the differences between congruency conditions when split into different-eye (masked) and same-eye (unmasked) conditions. The results revealed significantly lower accuracy for same-eye incongruent trials relative to same-eye no-flanker trials, *t* (23) = -3.10, *p* = .005, and for same-eye incongruent trials relative to same-eye congruent trials, *t* (23) = -3.23, *p* = .004; though accuracy was not significantly different between same-eye congruent trials and same-eye no-flanker trials, *t* (23) = .705, *p* = .488. No significant differences in accuracy were found when comparing the different-eye congruent trials and different-eye no-flanker trials, *t* (23) = 1.30, *p* = .206, the different-eye incongruent trials and different-eye no-flanker trials, *t* (23) = 1.66, *p* = .110, or the different-eye incongruent trials and different-eye congruent trials, *t* (23) = .43, *p* = .670. No significant differences in accuracy were found when comparing same-eye no-flanker trials and different-eye no-flanker trials, t (23) = .77, p = .450, or when comparing same-eye congruent trials with different-eye congruent trials, t (23) = -.01, p = .996; but accuracy was significantly lower for same-eye incongruent trials compared to different-eye incongruent trials, t (23) = -3.51, p = .002. These results suggest that accuracy dropped only during incongruent trials in the same-eye condition.

Discussion

The results indicate that a conflict effect, as assessed by both RTs and accuracy, is not elicited when the flanker arrows are shown to the eye opposite the CFS mask and target arrow (masked condition), but a conflict occurs when the flanker arrows are shown to the same eye as the CFS mask and target arrow (unmasked condition). The fact that there is no significant difference in RT between unmasked no-flanker trials and unmasked congruent trials in Experiment 2, despite significantly increased RTs for unmasked congruent trials relative to unmasked no-flanker trials in Experiment 1, might seem to suggest that the Mondrian images comprising the CFS mask aided in ignoring the flankers. Thus, the concerns motivating the implementation of Experiment 2 were warranted. However, because RTs increased and accuracy decreased significantly for incongruent trials in the same-eye condition (indicating a conflict effect), the lack of a conflict effect in the different-eye (masked) condition cannot be accounted for solely by the effects of the Mondrians. Rather, because the Mondrians were present for both masked and unmasked trials, the lack of a conflict effect in masked trials must result from the masking properties of CFS. The results thus corroborate the results from Experiment 1 and suggest that cognitive control is not elicited when participants are unaware of conflicting flanker information due to CFS masking.

FIGURE 3

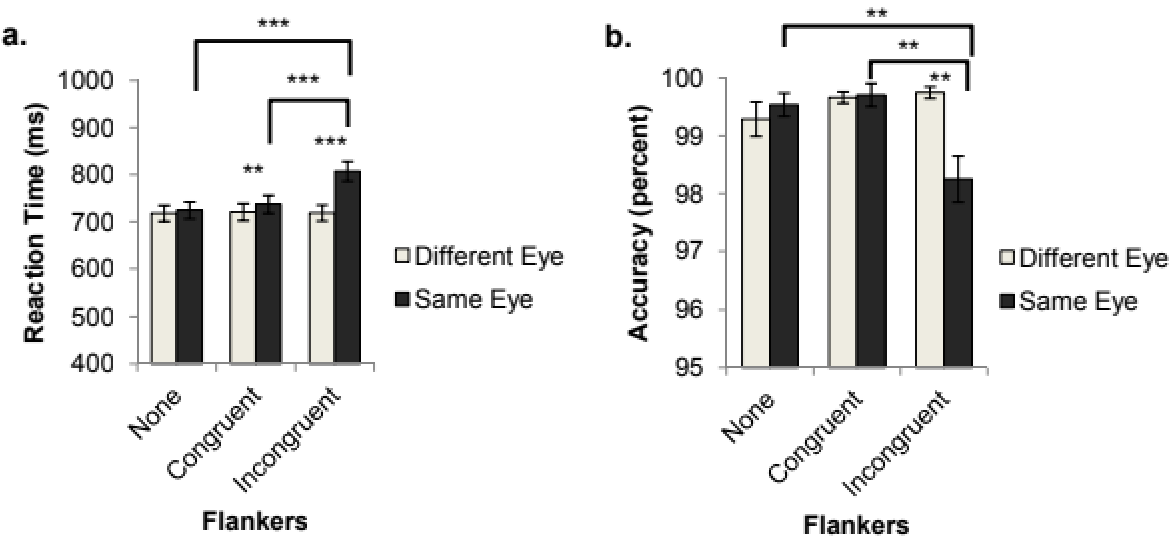

***Figure 3*. Behavioral data from Experiment 2.** (a) Reaction time (RT) and (b) accuracy are illustrated for Experiment 2. Incongruent trials in the same-eye (unmasked) condition led to increased RTs than no-flanker trials in the same-eye condition, congruent trials in the same-eye condition, and incongruent trials in the different-eye condition. Additionally, congruent trials in the same-eye condition led to increased RTs than congruent trials in the different-eye condition. Incongruent trials in the same-eye condition also led to lower accuracy than no-flanker trials in the same-eye condition, congruent trials in the same-eye condition, and incongruent trials in the different-eye condition.

* significant at $\alpha = .05$; ** significant at $\alpha = .01$; *** significant at $\alpha = .001$

CHAPTER 5: GENERAL DISCUSSION

If cognitive control could be elicited while masking awareness with CFS, a flanker conflict effect would be expected during masked trials of both experiments. However, the results from both experiments demonstrate that the flanker arrows elicited a conflict effect only in those trials without the CFS mask. No significant differences in RTs or accuracy were found in Experiment 1 for any of the masked flanker trials. However, RTs were significantly increased and accuracy decreased for unmasked incongruent trials. Likewise, no significant differences in RTs or accuracy were found in Experiment 2 for any of the different-eye (masked) flanker conditions, although RTs increased and accuracy decreased for the same-eye (unmasked) incongruent trials. The results provide evidence that cognitive control is elicited only when visual awareness of conflicting information is not suppressed.

Because attention and awareness are closely related, it is important to control for attention when manipulating awareness (Cohen, Cavanagh, Chun, & Nakayama, 2012; Marchetti, 2012; van Boxtel, Tsuchiya, & Koch, 2010). Experiment 2 demonstrated that the lack of conflict during masked trials was not due to the Mondrians diverting attention from the flanker arrows. Because CFS was always present in Experiment 2, no conflict effect would be expected in the same-eye (unmasked) condition if the results were a result of the Mondrians absorbing attention. However, because a conflict effect was seen in the same-eye condition, the lack of conflict during masked trials was likely due to suppression of visual awareness by CFS.

The results of these two experiments do not support earlier work demonstrating cognitive control effects without awareness (Lau & Passingham, 2007; Rahnev, et al., 2012; Reuss, et al., 2011; van Gaal, et al., 2010; van Gaal, et al., 2009) while corroborating work that shows a lack of cognitive control without awareness (Ansorge, et al., 2011; Boy, et al., 2010; Frings & Wentura, 2008; Heinemann, et al., 2009; Van den Bussche, et al., 2008). This may be due to differences in the specific cognitive control mechanisms tested in these studies (for a review, see Kunde, Reuss, & Kiesel, 2012). The present study elicited conflict using geometric shapes, i.e. the target and flanker arrows. It may not be possible to elicit shape-based conflict processing outside of awareness, as was found in the present study, despite the ability to elicit other forms of cognitive control. Therefore, it is important to note that these results may generalize only to the processing of conflicting shape information. More work is required to see if other paradigms, such as the Stroop task, can elicit a conflict effect while using CFS to mask stimuli.

Limitations of CFS

The possibility remains that the lack of conflict during masked trials is due to the presentation of the flanker and target arrows to separate eyes. Dichoptic presentations, which are necessary for CFS experiments, can elevate stimulus contrast thresholds and decrease flanker effect sizes (Maehara, Huang, & Hess, 2010). Further, masking low-contrast stimuli with CFS prevents primary visual cortex (V1) activation, similar to when no stimulus is presented at all (Yuval-Greenberg & Heeger, 2013). The lack of conflict during masked trials in the present study may thus reflect a change in contrast threshold of the flanker arrows (which were presented at a low-contrast for these experiments) and thus result in an inability of flanker information to reach V1. Because V1 has been implicated in shape contour processing (Kourtzi, Betts, Sarkheil, & Welchman, 2005; Li & Gilbert, 2002; Li, Piëch, & Gilbert, 2006), the lack of a conflict effect during masked trials in the present experiment may simply reflect a lack of shape processing (though shape processing may be seen in patients with V1 lesions; Marcel, 1998). Activation of V1 is likely a prerequisite for visual awareness (Koivisto, Mäntylä, & Silvanto, 2010; Tong, 2003), and so a lack of V1 activation could simply suggest successful masking. However, if CFS prevents low-contrast shape information from reaching V1, then the present results may not necessarily indicate that awareness is necessary for cognitive control. Rather, there may be a threshold of visual processing that needs to be reached, with or without awareness, to produce a conflict effect that elicits a greater degree of cognitive control.

Despite the evidence that CFS prevents information from reaching V1, information masked by CFS can be processed. Studies have demonstrated effects of masked stimuli during CFS, including processing of nude bodies (Jiang, Costello, Fang, Huang, & He, 2006) and performing simple math and reading (Sklar, et al., 2012). Subcortical pathways that bypass V1 may allow certain types of stimuli to affect behavioral responses even when masked by CFS. Recent fMRI work has implicated the involvement of subcortical pathways in processing face and object information masked by CFS and binocular rivalry (Fang & He, 2005; Pasley, et al., 2004; Troiani & Schultz, 2013). Thus, if subcortical processing is possible during CFS, the present results may indicate that subcortical processing is not sufficient to affect brain regions implicated in cognitive control, such as the anterior cingulate cortex and medial prefrontal cortex (Fan, et al., 2011; Ridderinkhof, et al., 2004; Ursu, et al., 2009; van Veen & Carter, 2002), or that subcortical structures cannot process flanker arrow shape information. However, neuroimaging work will be required to address this possibility within the present paradigm.

One possible avenue for future research is to perform the present experiments using a different form of masking, in particular one that selectively interferes with only regions further up in the visual processing stream. A newer technique referred to as “chromatic flicker fusion” (CFF) simultaneously presents two isoluminant and opposing colored stimuli to both eyes. The stimuli flicker in counter-phase with each other at a temporal frequency above the flicker fusion threshold (~30 Hz) (Hoshiyama et al., 2006). Although CFS and CFF can render stimuli subjectively invisible with supposedly comparable effectiveness, unconscious information that never leaves the occipital lobe using CFS can show effects within temporal and frontal regions using CFF (Fogelson et al., 2014). Thus, CFF may be a more sensitive technique for measuring unconscious high-level processing than CFS. Performing similar experiments as the ones outlined here with different masking paradigms and with different categories of stimuli, in conjunction with functional neuroimaging techniques, may help shed further light on the necessary and sufficient conditions for information to have a measurable effect on cognitive control.

Defining and Measuring Awareness

It is possible that the inconsistencies in previous work addressing cognitive control without awareness are due to the methods used to manipulate awareness. Different masking paradigms can lead to opposing conclusions, despite it being agreed that participant awareness is successfully suppressed with each paradigm (Almeida, Pajtas, Mahon, Nakayama, & Caramazza, 2013). It has been suggested that stronger masking paradigms are more effective for suppressing awareness (Almeida, et al., 2013; Desender & Van den Bussche, 2012). However, this suggestion seems to be based on the assumption that any sub-threshold processing that may be seen with weaker masking paradigms necessarily constitutes awareness, which may not be true (Merikle, Smilek, & Eastwood, 2001).

In addition, currently there is no completely reliable means of measuring awareness. Although subjective and objective measures are often used to test participant awareness, they both depend on strong underlying assumptions regarding which behaviors and responses constitute awareness. Objective forced-choice measures assume that accuracy above chance indicates awareness (Hesselmann, et al., 2011; Van Opstal, et al., 2011). However, both hemi-neglect and blindsight patients are able to discriminate objects above chance in forced-choice measures, despite their apparent lack of awareness of those objects (Driver & Mattingley, 1998; Marcel, 1998), and there is evidence for similar effects in healthy groups (Hesselmann, et al., 2011). Forced-choice measures therefore may be too conservative to serve as indicators of awareness when used alone and may conflate sub-threshold processing with access to awareness (Merikle, et al., 2001).

Subjective reports, in contrast, involve a free response by participants to indicate some feature of a masked stimulus (e.g. its presence or identity). Subjective measures define awareness as a participant’s ability to successfully identify a stimulus or otherwise freely indicate that something was seen (Dienes & Scott, 2005). However, there are unique concerns with this approach. Participants often have differences in their criteria for reporting awareness (Merikle, 1984; Persaud, McLeod, & Cowey, 2007), and it is possible that participants are aware of more than they can verbally report due to limits of attention or memory (Block, 2011; DeGardelle, 2009; Fei-Fei & Perona, 2007; Li, Vanrullen, Koch, & Perona, 2002; Sperling, 1960; van Boxtel, et al., 2010). Thus, more objective measures of defining awareness, such as the behavioral data in the present experiments, may be seen as more robust and replicable, though at the risk of being overly strict in defining awareness.

The above issues highlight the difficulty in defining awareness in a way that separates it from related functions. Conscious visual awareness is not necessarily an all-or-none, discrete phenomenon that serves as the culmination of processing in particular brain regions or networks (Cohen, et al., 2012; Dehaene & Naccache, 2001; Mole, 2008; Tallon-Baudry, 2011; Tononi & Koch, 2008; van Boxtel, et al., 2010). Masking paradigms may operate at different stages of visual processing (Almeida, et al., 2013; Troiani & Schultz, 2013), making it difficult to determine which method is the best for manipulating awareness. Sensory input, working memory, internal self-representation, and attention are all components of awareness, and interrupting any of those processes will cause an interruption in awareness (Marchetti, 2012). Because all masking paradigms interrupt further processing of visual information at some stage (otherwise they would not prevent visual awareness), the cutoff for determining when awareness “happens” is arbitrary. Although it is useful to illustrate the degree of processing that is possible when one component of awareness is suppressed, whether or not the processing should be considered “awareness” is a matter of semantics. In the present experiments, if there had been a blindsight-like effect during the fifth runs as well as a positive result on masked trials, it may have been possible to argue that the participants had in fact been aware of the masked stimuli, and perhaps an effect of attention or memory prevented them from reporting their awareness.

Conclusions

Though the results of the present study could suggest that awareness is necessary for cognitive control, as suggested by previous work (Ansorge, et al., 2011; Boy, et al., 2010; Frings & Wentura, 2008; Heinemann, et al., 2009; Van den Bussche, et al., 2008), they do not allow definitive conclusions. The present results indicate that cognitive control, in the form of conflict resolution, does not appear to be involved when masking flanker arrows, even if the masked stimuli are presented for a duration of time that should allow for sufficient processing time.

Based on the above considerations, awareness is currently too vague of a concept to be manipulated unambiguously using one preferred masking technique. Because awareness may broadly refer to how an information-processing system like the brain integrates and understands its own processing as it interacts with the world (Crick & Koch, 2003; Metzinger, 2000), it may be the case that awareness is a general term that encompasses several related and integrated functions (Marchetti, 2012). Therefore, future research should address which brain regions and functions are suppressed when using different masking paradigms, rather than treating "awareness" as a fundamental process. Neuroimaging techniques may elucidate which functions are interrupted during different masking paradigms (Yuval-Greenberg & Heeger, 2013) as well as alternative processing pathways (Troiani & Schultz, 2013). Likewise, assessing neural differences during objective and subjective measures of awareness may lead to a more concrete operational definition of awareness (Hesselmann, et al., 2011). Until more work is done, it is unclear if cognitive control can be elicited without awareness. However, the present results suggest that cognitive control cannot be elicited when CFS is used to prevent awareness of conflicting information.

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