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OBSERVATION

Re-Examining the Influence of Attention and Consciousness on Visual Afterimage Duration

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The relationship between visual attention and conscious perception has been the subject of debate across a number of fields, including philosophy, psychology, and neuroscience. Whereas some researchers view attention and awareness as inextricably linked, others propose that the two are supported by distinct neural mechanisms that can be fully dissociated. In a pioneering study, van Boxtel, Tsuchiya, and Koch (2010b) reported evidence for a dissociation between attention and conscious perception using a perceptual adaptation task in which participants' perceptual awareness and visual attention were manipulated independently. They found that participants' awareness of an adapting stimulus increased afterimage duration, whereas attending to the adaptor decreased it. Given the important theoretical implications of these findings, we endeavored to replicate them using an identical paradigm while dealing with some potential shortcomings of the original study by adding more trials and a larger participant sample. Consistent with van Boxtel, Tsuchiya, and Koch, we found that afterimage duration was reliably increased when participants were aware of the adapting stimulus. In contrast to the original findings, however, attention to the adaptor also increased afterimage duration, suggesting that attention and awareness had the same—rather than opposing—effects on afterimage duration. We discuss possible reasons for this discrepancy.

Public Significance Statement

Considerable research has been devoted to understanding the nature of conscious visual experience and the processes that regulate it. Traditionally, mechanisms of attention have been assumed to play a critical role in determining whether a sensory event is experienced consciously. Specifically, it is assumed that stimuli that are attended enter awareness, whereas those that are ignored do not. More recently, however, it has been suggested that focused attention is not required for conscious perception. Here we attempted to replicate an influential study that demonstrated that attention to, and awareness of, a visual adapting stimulus had opposing effects on the duration of the induced afterimage. Using the identical stimuli and experimental set-up, but with enhanced statistical power, we failed to replicate the attention effect and showed instead that attention and awareness have the same effect on perception.

Keywords: attention, consciousness, continuous flash suppression, afterimage

There has been considerable debate in the literature on visual perception as to the relationship between attention and consciousness. Here we define attention as those processes that prioritize some sensory inputs over others and consciousness as the reportable contents of a perceptual experience. Whereas the terms consciousness and awareness are often used interchangeably, here we use the more specific term perceptual awareness[1] (or just awareness; Cohen, Cavanagh, Chun, & Nakayama, 2012; Kim & Blake, 2005; van Boxtel, Tsuchiya, & Koch, 2010a). Although some argue that attention is necessary for awareness (e.g., Carrasco, Ling, & Read, 2004; Reynolds & Desimone, 2003; Treue, 2003), others propose that these processes are supported by distinct neural mechanisms that can be fully dissociated (e.g., Koch & Tsuchiya, 2007; van Boxtel et al., 2010a, 2010b; Wyart & Tallon-Baudry, 2008).

Several previous studies have found that attending to a visual adapting stimulus reduces the duration of its afterimage (Bras-

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[1] We follow Kanwisher (2001) in defining perceptual awareness as the extraction of perceptual information from a stimulus that is experienced consciously.

camp, van Boxtel, Knapen, & Blake, 2010; Suzuki & Grabowecky, 2003; van Boxtel et al., 2010b; Wede & Francis, 2007). For example, in one prominent and widely cited study, van Boxtel et al. (2010b) had observers report the duration of an afterimage after they had been exposed to a peripheral Gabor (the adaptor) that was either visible or was rendered invisible using continuous flash suppression (CFS; Gilroy & Blake, 2005; Tsuchiya & Koch, 2005; Tsuchiya, Koch, Gilroy, & Blake, 2006). During adaptation, observers also undertook a central visual attention task that was either easy (low load), allowing limited perceptual resources to spill over to the adaptor, or difficult (high load), leaving little or no capacity for processing of the adaptor (Bahrami, Carmel, Walsh, Rees, & Lavie, 2008; Lavie, 1995; Lavie, Hirst, de Fockert, & Viding, 2004; Macdonald & Lavie, 2008). The authors found that their observers' afterimages lasted longer when the adaptor was visible than when it was invisible. By contrast, afterimage duration was reduced under low- versus high-central load, implying that any residual attentional resources available for processing the adapting stimulus actually reduced the influence of the adapting stimulus on afterimage duration. In a further experiment, the authors varied the visibility of the adapting Gabor by manipulating the contrast of the CFS mask and again found that afterimage duration increased with awareness of the adaptor but was reduced under low attentional load. van Boxtel and colleagues concluded that attention and awareness are independent processes, based on the opposing effects they exert on afterimage duration, consistent with conclusions from previous investigations (Bachmann & Murd, 2010; Brascamp et. al., 2010; Lou, 2001; Suzuki & Grabowecky, 2003; Wede & Francis, 2007; Wyart & Tallon-Baudry, 2008).

Given the influential contribution of the findings of van Boxtel et al. (2010b) to the attention versus awareness debate, we aimed to replicate their key results. In Experiment 1 we set out to replicate Experiment 2a from their paper. The authors kindly sent us their experimental code so we could reproduce their stimuli with high fidelity. Trial number and sample size were small in the study by van Boxtel and colleagues, an issue we return to in the Discussion, so we increased these. Critically, we also included an awareness test to verify the effectiveness of the masking stimulus, a manipulation check not included in the original study. No changes were made to the critical experimental conditions or event timing. In Experiment 2, we sought to replicate Experiment 3 from the study by van Boxtel et al. (2010b), again adhering strictly to their original protocol.

Experiment 1

Method

Participants. Twenty individuals (11 females; mean age = 23.61 years, *SD* = 4.63) participated. All reported normal or corrected-to-normal vision, were naïve to the experimental hypotheses, and provided informed written consent. The University of Queensland Human Research Ethics Committee approved the studies.

Stimuli and Apparatus

Stimuli were presented on a 24-inch LCD monitor (refresh rate 60 Hz, mean background luminance 51 cd/m^2, without gamma correction). Stimulus delivery and response recording were controlled using a Dell PC running Cogent software (Cogent, 2000; toolbox: Functional Imaging Laboratory, Institute of Cognitive Neuroscience, and Wellcome Department of Imaging Neuroscience, London, UK) in Matlab (The MathWorks, Inc., Natick, MA) under Windows XP. Participants viewed dichoptic displays through a mirror stereoscope at a viewing distance of ~57 cm.

Stimuli, which were identical to those used in Experiment 2a of van Boxtel et al. (2010b; Figure 1), were displayed against a uniform gray background (see Figure 1). During the entire presentation, a white fixation dot was presented to both eyes. Each trial began with a 4-s adaptation phase. The adaptor was a gray-scale 34% Michelson-contrast Gabor (carrier spatial frequency = 0.23 cycles per degree). The full width at half height of the Gaussian envelope was 1.43°. Gabor orientation was randomly assigned on each trial. During adaptation the Gabor was presented to one eye (counterbalanced) 4.9° from the central fixation dot in one of eight cardinal or intercardinal directions. To minimize carryover adaptation from previous trials, the location of the Gabor shifted counterclockwise by 45° between trials. On half of the trials, the CFS mask was presented to the other eye. The mask was a black (1.4 cd/m^2) and white (214 cd/m^2) Gaussian-windowed (σ = 1.43°) checkerboard (0.78 cycles per degree) that counterphased (every 67 ms) and continuously rotated (150 °/s).

Fifteen colored crosses [red International Commission on Illumination (CIE .607, .365, 42.9 cd/m2), green (CIE .294, .651, 158 cd/m^2), blue (CIE .144, .083, 16.7 cd/m^2), yellow (CIE .396, .561, 198 cd/m^2), cyan (CIE .226, .395, 173 cd/m^2), and magenta (CIE .314, .184, 57.2 cd/m^2)] measuring 1.9° in height and 1.4° in width were presented at 3.76 Hz binocularly at fixation.

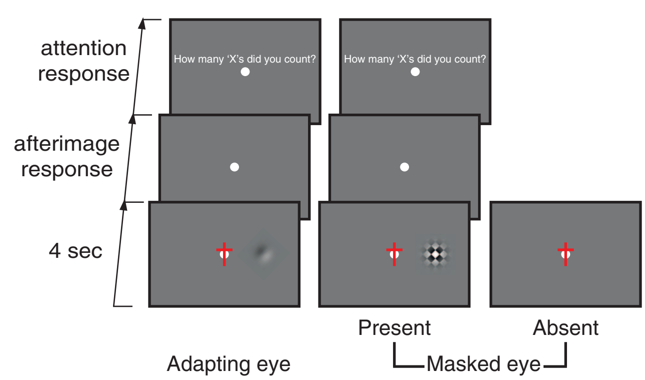

Figure 1. Schematic of displays used in Experiment 1. Each trial began with a 4-s adaptation phase. The adaptation stimulus was a peripheral Gabor patch. Attention was manipulated by a central rapid serial visual presentation (RSVP) task, in which observers were required to count the number of upright and inverted red crosses (low load) or upright yellow and inverted green crosses (high load). Visibility of the adaptor was manipulated by presenting a rotating and counterphasing checkerboard mask to the eye contralateral to the adapting stimulus (unaware condition), or no mask was presented (aware condition). After the adaptation phase, observers indicated afterimage duration by pressing and releasing a mouse button. After recording afterimage duration, observers reported the number of targets presented out of a possible four targets. See the online article for the color version of this figure.

Procedure

Participants performed 16 practice trials, followed by eight blocks of 16 experimental trials. During adaptation, attention was manipulated by a rapid serial visual presentation (RSVP) task in which participants counted the number of upright and inverted red crosses (low load), or upright yellow and inverted green crosses (high load; see Schwartz et al., 2004). Target numbers on each trial could be 1, 2, 3, or 4 and were separated by at least one nontarget. After adaptation, participants indicated the duration of their afterimage using a mouse held in the right hand. They then used their left hand to indicate on a keyboard the number of targets. Accuracy feedback was provided during practice but not during the experiment.

Awareness Test

Following the experiment, participants performed four blocks of 16 awareness test trials. Here stimuli were identical to those in the experimental trials, except that there was no RSVP stream, and a counterphasing mask was presented for 100 ms after the Gabor to reduce any afterimage at that location. A second Gabor was then presented at fixation in a random orientation. On half the trials, the initial Gabor was masked using CFS, and on the other half of trials there was no CFS mask. Participants used a mouse to rotate the second Gabor to match the orientation of the first Gabor.

Results

Two participants were excluded from the analysis because their accuracy in the attention task was not significantly above chance (25%). Overall RSVP accuracy was well above chance (25%) for both the low-load (77.17%), $t(17) = 533.99$, $p < .001$, and high-load (59.03%) tasks, $t(17) = 730.07$, $p < .001$. Accuracy was also significantly higher in the low- than in the high-load task, $t(17) = 6.17$, $p < .001$, 95% confidence interval (CI) [11.94, 24.34], confirming the effectiveness of the load manipulation.

Afterimages persisted for longer when participants were aware of the adapting Gabor (no CFS) than when they were unaware of it (CFS; Figure 2). Likewise, afterimages lasted longer in the low-load than in the high-load condition. This difference in afterimage duration with attention is in the opposite direction to that reported by van Boxtel et al. (2010b).

Mean afterimage durations were calculated for each participant in each condition, excluding incorrect responses. Responses greater than 3 *SD* above the participant's mean for each condition were removed (~68% of all trials were included). Mean afterimage durations were then subjected to a repeated-measures analysis of variance (ANOVA) with the factors of adaptor condition (aware, unaware) and attentional load (low load, high load). There was a significant main effect of adaptor condition, $F(1, 17) = 12.10$, $p = .003$, $\eta_p^2 = .416$, 95% CI [229.33, 936.14]. Mean afterimage duration was 582 ms longer for aware trials ($M = 2262$ ms, $SD = 977$) than for unaware trials ($M = 1680$ ms, $SD = 876$).

There was also a significant main effect of attentional load, $F(1, 17) = 5.47$, $p = .032$, $\eta_p^2 = .243$, 95% CI [13.01, 252.43]. Mean afterimage duration was shorter for high-load ($M = 1905$ ms, $SD = 968$) than for low-load trials ($M = 2037$ ms, $SD = 930$). This effect was opposite to that reported by van Boxtel et al. (2010b). Adaptor condition and attentional load did not interact, $F(1, 17) = .63$, $p = .438$, $\eta_p^2 = .036$.

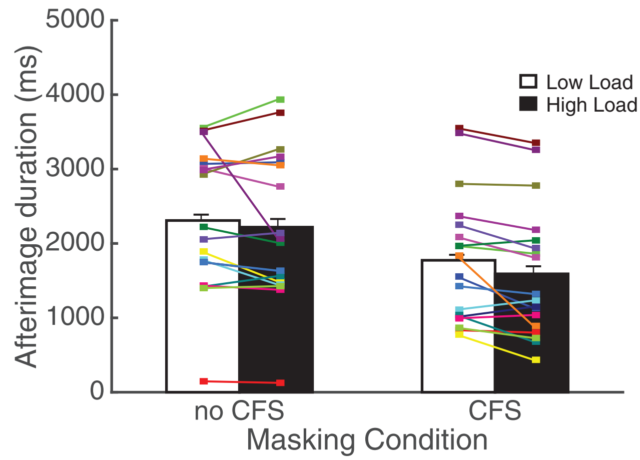

Figure 2. Mean afterimage duration in Experiment 1. Aware (no continuous flash suppression [CFS]) trials produced longer afterimage durations than unaware (CFS) trials. Afterimage duration was reduced under high-attentional load relative to low-attentional load conditions. Colored squares indicate mean responses for individual participants. Error bars represent within-subjects standard errors of the means (Masson & Loftus, 2003). See the online article for the color version of this figure.

Awareness Test

Orientation judgments in the awareness test—normalized to the orientation of the first Gabor—were randomly distributed for the condition in which the CFS mask was present (Figure 3A) and aligned close to zero degrees (perfect performance) on trials in which no mask was presented (Figure 3B). We calculated the difference in orientation between the first and the second Gabors and then tested these distributions for uniformity. A V test for nonuniformity, with a mean direction of 0 radians, showed that the population of responses was uniformly distributed around the circle for CFS trials ($v = 19.907$, $p = .120$) but was not distributed uniformly for non-CFS trials ($v = 483.228$, $p < .0001$). The mean resultant vector for non-CFS trials was .90 (median = .40).

Experiment 2

Experiment 2 was an exact replication of Experiment 3 from van Boxtel et al. (2010b), in which the contrast of the CFS mask—and thus the visibility of the adapting Gabor—was varied across trials.

Method

Participants. Twenty new individuals (16 females; mean age = 23.44 years, $SD = 5.40$) participated.

Stimuli, Apparatus, and Procedure

The methods were the same as those of Experiment 1, except that the CFS mask was presented at eight different contrast levels (0%, 1.6%, 3.1%, 6.3%, 12.5%, 25%, 50%, and 100%), and after

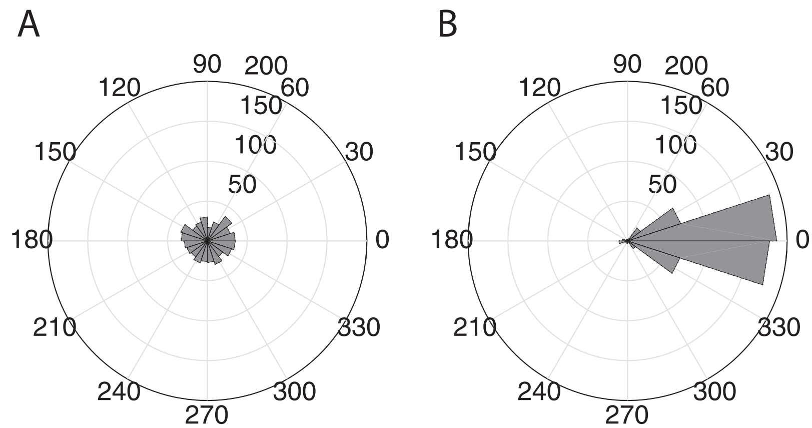

Figure 3. Polar plot showing the distribution of normalized directional orientation judgments in the awareness test. Values are grouped in 20 bins according to their angular range in polar coordinates. The angle of each bin represents the difference in degree between the orientation of the first Gabor and participants' orientation choice. The extent of each bin represents the number of trials that fall within each bin. Participant orientation responses were random with respect to the alignment of the initial Gabor on trials in which the continuous flash suppression (CFS) mask was present (A) but were well aligned on trials in which the CFS mask was absent (B).

the practice, participants completed two sessions, each of which consisted of eight blocks of 32 trials.

Results

Attention and awareness again had similar effects on afterimage duration, as in Experiment 1 but contrary to the findings of van Boxtel et al. (2010b). As shown in Figure 4, afterimage duration decreased with increases in mask contrast, and afterimage duration was longer under low attentional load than under high load.

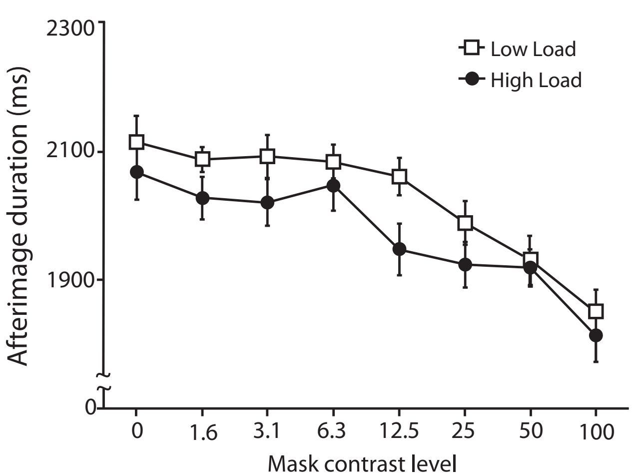

Figure 4. Mean afterimage duration in Experiment 2. Afterimage duration varied as a function of awareness, such that low rates of awareness (i.e., higher contrast continuous flash suppression (CFS) masks) produced shorter afterimages than high rates of awareness. The CFS mask was presented at eight different contrast levels (0°, 1.6°, 3.1°, 6.3°, 12.5°, 25°, 50°, and 100%). Afterimage duration was shorter under high-central load compared with low-central load conditions. Error bars represent within-subjects standard errors of the means (Masson & Loftus, 2003).

Overall RSVP accuracy, pooled across the different contrast levels, was above chance for both the low- (87%), $t(19) = 857.96$, $p < .001$, 95% CI [81.18, 92.96], and high-load (69%), $t(19) = 562.22$, $p < .001$, 95% CI [60.46, 78.56] conditions. Accuracy was also significantly higher in the low- than in the high-load task, $t(19) = 4.25$, $p < .001$, 95% CI [8.91, 26.21] (paired-samples *t* test).

After removing incorrect trials and outliers (~22% of trials removed; see Experiment 1 for procedure), mean afterimage duration was subjected to a repeated-measures ANOVA with the factors of adaptor condition (eight contrast levels) and attentional load (low load, high load). There was a significant main effect of adaptor condition, $F(7, 133) = 10.61$, $p < .001$, $\eta_p^2 = .358$, $BF_{10} = 1.718e + 10$. Null-hypothesis testing revealed no statistical difference in afterimage duration for the low- ($M = 2026$ ms, $SD = 883$) versus high-load ($M = 1971$, $SD = 908$) conditions, $F(1, 19) = 3.17$, $p = .091$, $\eta_p^2 = .143$, 95% CI [−9.68, 119.85]. We also performed a Bayes factor analysis using JASP (version 0.8.0.0, https://jasp-stats.org/) to quantify the strength of evidence for the null hypothesis. The Bayes factor for the main effect of attentional load was $BF_{10} = 4.133$. Thus, whereas the inferential analysis suggested no effect of attentional load, the Bayes factor analysis revealed that attention did moderately increase afterimage duration. Critically, however, there was no evidence that attention decreases afterimage duration. There was also no interaction between adaptor condition and attentional load, $F(7, 133) = .56$, $p = .787$, $\eta_p^2 = .029$. An ANOVA on Bayes factors revealed that the main effects model was preferred to the interaction model by a factor of 51.22.

Discussion

Here we sought to replicate an influential and widely cited study by van Boxtel et al. (2010b), in which the authors found that visual attention and awareness have opposing effects on perceived afterimage duration. Specifically, van Boxtel and colleagues found that afterimage duration increased when observers were aware (vs. unaware) of the adapting stimulus but decreased when residual attention was available for processing the adaptor, compared with a condition in which attention was fully expended on a central visual task. We replicated two of the key experiments from the original study and found instead that attention and awareness both increased afterimage duration.

Our finding that attention increased afterimage duration is in contrast with the findings of van Boxtel et al. (2010b), as well as other studies that used different stimuli and experimental protocols (e.g., Brascamp et. al., 2010; Suzuki & Grabowecky, 2003; Wede & Francis, 2007) and found that attention decreased afterimage duration. In this context, we note the work of Baijal and Srinivasan (2009), which suggests that perceived afterimage duration is sensitive to the particular type of attention directed toward the inducing stimulus. In light of this previous research, we would conclude that although the present results suggest that attention does not decrease afterimage duration, we acknowledge that afterimage durations are evidently decreased in other experimental contexts. Further work will be required to determine what kinds of stimuli, tasks, and attention manipulations are required to yield such reliable reductions.

Given the theoretical importance of the study by van Boxtel et al. (2010b) and our failure to replicate the opposing effect of attention and awareness they observed, it is important we consider some of the factors that might have led to the discrepant findings. One explanation comes from work by Brascamp et. al. (2010), who suggested that the enhanced adaptation that accompanies attention to a stimulus can simultaneously facilitate the formation of an afterimage, thereby increasing afterimage duration, and augment the elevation of the observer's detection threshold, thereby decreasing (perceived) afterimage duration. It is possible that the balance between these two putative effects was different for our study and that of van Boxtel et al., which might in turn have caused the differential effects of attention on afterimage duration. Given that we used the same stimuli and the same experimental procedures as van Boxtel et al. (2010b) however, this seems somewhat unlikely.

Another possibility is that the experiments in the study by van Boxtel et al. (2010b) were statistically underpowered, both in terms of the number of participants tested and the number of trials included in the critical conditions (see Table 1). An a priori power analysis performed with G*Power, for the main effect of attention on afterimage duration (f = .30, and α-error equal to .05, and a power of .80) calls for a sample size of 24 participants. The sample size used in van Boxtel et al. (2010b) was eight in Experiment 2a and nine in Experiment 3. As the sampling distribution for a low-powered study is typically wider than the sampling distribution for a high-powered study, the sample mean needs to be larger in a low-powered study to reject the null hypothesis. Thus, a statistically significant finding from a low-powered study is more likely to overestimate the effect size when compared with a statistically significant finding from a high-powered study (Button et al., 2013). It should be noted in this context that our own study was also somewhat underpowered—we included data from 18 and 20 participants in Experiments 1 and 2, respectively—although considerably less so than in the original investigation.

Table 1
Number of participants and trials in Van Boxtel et al. (2010b)

Experiments	N	Trials per cell	Mean trials per cell in analysis
Experiment 2a	8	16	~13.6
Experiment 3	9	8	~5.6

A second possible reason for the discrepant findings concerns the relatively low trial numbers used in the study by van Boxtel et al. (2010b; see Table 1). In their Experiment 3, for example, participants performed only eight trials in each condition, which would likely have yielded a somewhat imprecise estimate of the true afterimage duration. Moreover, after removing incorrect trials, data from only approximately six trials per condition were included in the final analysis. In the current study, after removing incorrect trials and outliers, data from ~22 trials (Experiment 1) and ~25 trials (Experiment 2) per condition were included in the final analysis, potentially improving estimates of observers' true performance in each condition.

In summary, our findings suggest attention and awareness have similar, rather than opposing, effects on afterimage duration, at least within the context of the specific paradigm introduced by van Boxtel and colleagues (2010b). Whereas our failure to replicate suggests caution in using this specific approach to support the argument that attention and awareness are dissociable processes, there is nevertheless a diverse literature in support of this general conclusion (for reviews see Koch & Tsuchiya, 2007; Tallon-Baudry, 2012). Future work should be directed toward understanding the specific conditions under which attention and awareness operate together or in opposition. Such investigations will provide important insights into the relationship between attention and awareness in human vision.

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