Priming of object detection under continuous flash suppression depends on attention but not on part-whole configuration

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Previous research has shown that the identification of visual objects can rely on both view-dependent, holistic as well as view-independent, analytic representation, depending on visual attention. Here, we asked whether the initial conscious detection of objects reveals similar dependencies and may therefore share similar perceptual mechanisms. We used continuous flash suppression to render objects presented in familiar views invisible at the beginning of a trial and recorded the time these target objects needed to break into awareness. Target objects were preceded by spatially attended or unattended primes that were either shown in the same familiar view as the targets or horizontally split (i.e., with their halves swapping positions) in order to disrupt holistic processing. Relative to an unprimed baseline, suppression times were shorter for all priming conditions. Although spatial attention enhanced this priming effect on access to awareness, even unattended primes facilitated awareness of a related target, indicating that object detection does not fully concur with the idea of attention-demanding analytic object representations. Moreover, priming effects were of similar strength for primes shown in the same familiar view as the targets and for horizontally split primes, indicating that holistic (template-like) representations do not play an integral role in object detection. These results suggest that the initial detection of an object relies on representations of object features rather than holistic representations used for recognition. The perceptual mechanisms mediating conscious object detection are therefore markedly different from those underlying object identification.

Introduction

Visual perception of objects involves a hierarchy of processing stages, from initial image segmentation and conscious object detection to object categorization, identification, and naming. Much work has been carried out on the perceptual mechanisms underlying the more advanced levels of this hierarchy, with a focus on object recognition in particular. One particular question attracted much research in the last 25 years: Given that an object can cast dramatically different two-dimensional (2-D) images on the retina when seen in different views, are the memory representations underlying view constancy also based on stored 2-D

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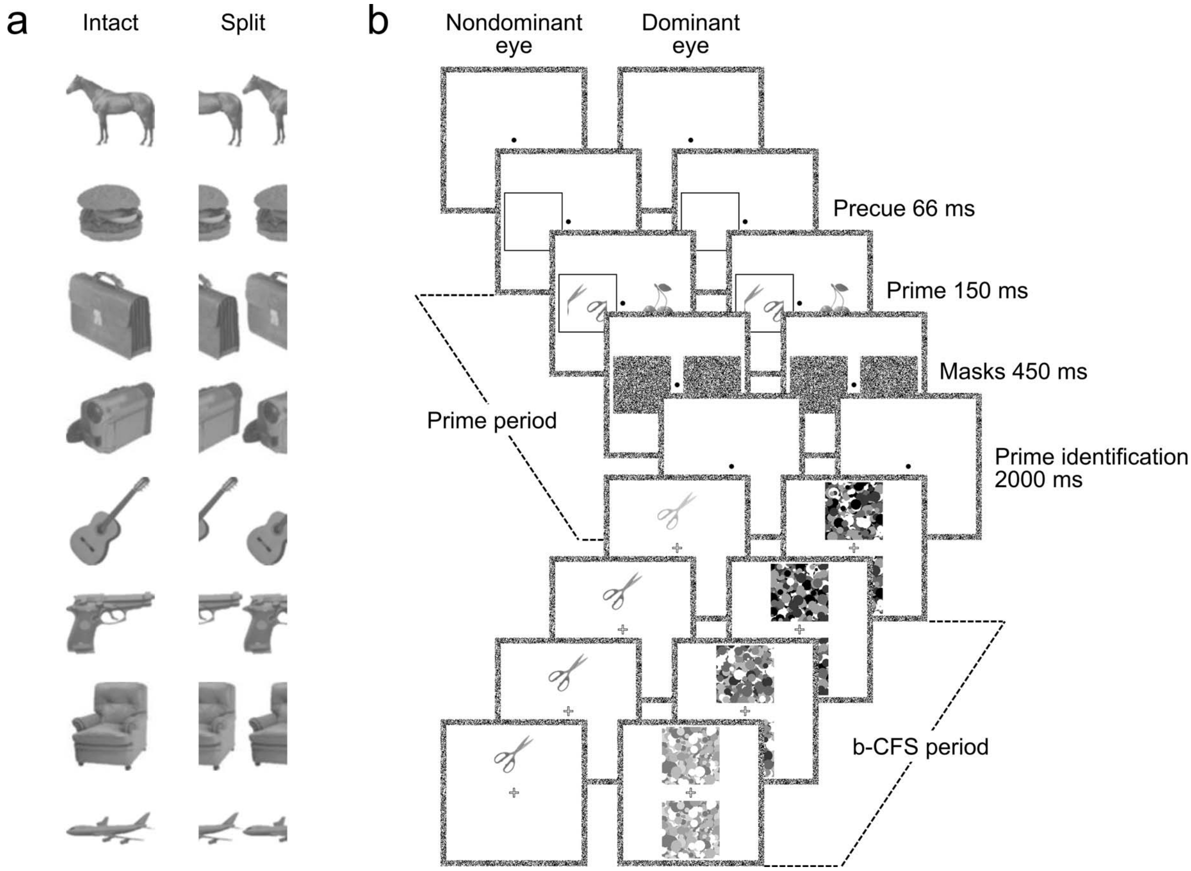

Figure 1. (a) Example stimuli. (b) Schematic of an example trial. In the priming period, stimuli were presented binocularly, and participants covertly named the cued object. In the b-CFS period, participants localized a target object that was initially rendered invisible through interocular suppression.

representations (e.g., Bülthoff & Edelman, 1992; Tarr, 1995)? The idea of holistic (all-in-one-piece) view-based representation would fit data showing that recognition performance decreases when objects are rotated from familiar views (for reviews, see Hummel, 2013; Peissig & Tarr, 2007). Alternatively, objects may be represented analytically (meaning that attributes such as parts and their spatial relations are independent from each other) and stored as more abstract collections of generalized three-dimensional (3-D) parts, which allow the identification of an object from any 2-D image, and therefore independently of viewpoint (Biederman, 1987; Hummel & Biederman, 1992). Recently, researchers seem to agree that the brain uses both view-dependent as well as analytic representations, with at least one influential theory claiming that analytic representations are only established when objects have received spatial attention (Hummel, 2001).

To investigate whether object recognition is mediated by such a hybrid representation that can be both view- and part-based, which in turn depends on the allocation of attention, Thoma, Hummel, and Davidoff (2004) used a short-term priming paradigm with yoked prime and probe displays. In the prime displays two objects were shown briefly to the left and the right of fixation, with only one object receiving the participants' attention by visually precueing the side it appeared on. In a subsequent probe display a single target object shown in a familiar view had to be identified, which was the previously attended, the unattended, or an unrelated object (to establish the baseline for recognition). Thoma and colleagues (2004) found that attended objects produced reliable priming even when the prime object was shown in a different view, that is, configurally distorted ("split," see Figure 1a). In contrast, unattended objects produced reliable priming only when they were repeated in the same (familiar) view. These and similar findings with objects rotated in the picture plane (Thoma & Davidoff, 2006; Thoma, Davidoff, & Hummel, 2007) are in line with predictions of the hybrid model of object recognition by Hummel (2001) proposing that when objects are attended, they are not only encoded in their seen viewpoint (as is automatically the case for unattended objects), but also as an ensemble of parts and spatial relations (also known as analytic representations, Hummel & Biederman, 1992; or as structural descriptions, Biederman, 1987; Marr & Nishihara, 1978). The hybrid model therefore not only explains previous apparently contradictory findings on view-dependency (for a review, see Peissig & Tarr, 2007; Thoma & Davidoff, 2007) but also generates novel predictions, for example, on priming effects after scaling (Stankiewicz & Hummel, 2002) and depth rotations (Thoma & Davidoff, 2006).

While these studies support a hybrid model for object *recognition* (what object is it?), much less is known about the perceptual mechanisms underlying the initial conscious *detection* of an object in the visual field (is an object there?) and how they depend on attention. The initial conscious detection of an object is usually assumed to precede recognition (Nakayama, He, Shimojo, 1995) and to depend less on top-down influences such as prior knowledge (Theeuwes & Van der Burg, 2007). However, there is some evidence that object detection and recognition can happen at the same time (Grill-Spector & Kanwisher, 2005), indicating that detection and recognition may share similar perceptual mechanisms. More recent work, by contrast, has supported the traditional view of detection preceding recognition, with distinct mechanisms guiding detection and recognition (Mack & Palmeri, 2010). For example, Mack, Gauthier, Sadr, and Palmeri (2008) showed that degrading the image of an object has a stronger effect on recognition than on detection. However, to our knowledge no study has directly looked at whether object detection—rather than object recognition—is modulated by attention and by view-changes. Answering this question will advance our understanding of the nature of the initial processing stages in visual object perception and clarify to what extent the simple detection of an object is influenced by top-down processes. If detection and object recognition rely on similar processes, then we would expect similar effects of attention and view-changes on priming of object detection as have been found for priming of object identification (Thoma et al., 2004).

To measure priming effects in simple detection, we presented objects under strong interocular suppression induced by continuous flash suppression (CFS; Tsuchiya & Koch, 2005). In CFS, a high-contrast pattern mask flashed into one eye can render a photograph of an object presented to the other eye invisible for several seconds (Figure 1b). The time it takes for a target object to overcome CFS and break into awareness represents a highly sensitive measure of stimulus detectability (Jiang, Costello, & He, 2007) that opens a unique window into the perceptual processes at the transition to conscious perception (Gayet, Van der Stighel, & Paffen, 2014; Stein, Hebart, & Sterzer, 2011; Stein & Sterzer, 2014). Recently, this breaking-CFS paradigm (b-CFS; Stein, Hebart, & Sterzer, 2011) has been used to reveal previously unknown stimulus- and observer-related factors that determine access to awareness for complex naturalistic objects (for a review, see Gayet et al., 2014). For example, suppression times are shorter for familiar photographs of faces (Gobbini et al., 2013) and for faces and human bodies presented in their familiar upright orientation (Jiang et al., 2007; Stein, End, & Sterzer, 2014; Stein, Peelen, & Sterzer, 2011; Stein, Sterzer, & Peelen, 2012; Zhou, Zhang, Liu, Yang, & Qu, 2010). Moreover, breakthrough into awareness can be facilitated by actively retaining target-related information in working memory (Gayet, Paffen, & Van der Stighel, 2013; Pan, Lin, Zhao, & Soto, 2014) and by priming from prior, consciously accessible information related to the suppressed target (Costello, Jiang, Baartman, McGlennen, & He, 2009; Lupyan & Ward, 2013). Thus, b-CFS represents a powerful device for measuring the influence of priming on the initial conscious detection of naturalistic objects.

In the present study, we used b-CFS to measure the influence of attention on analytic and holistic processing in object detection. We recorded suppression times for target objects presented in familiar views that were preceded by two briefly presented visible object primes, one of which was spatially precued (attended) and one of which was uncued (unattended). A prime object was either intact (shown in the same familiar view as the target object) or horizontally split (with its halves swapping positions, see Figure 1a). Thus, we used the same attention and prime stimulus manipulations that have been shown to influence object identification in a way predicted by the hybrid theory of object recognition (Thoma et al., 2004). Importantly, splitting an object image is more than a view change such as rotating an object in the picture plane or in depth. A split image cannot be fully matched to a potential holistic (view-like) representation in memory, as it is by definition not a view (Hummel, 2001; Ullman & Basri, 1991). At the same time, a split image would still be recognizable by part-based representations as proposed by Biederman and colleagues (Biederman, 1987; Hummel & Biederman, 1992). Please note that the degree to which splitting interferes with holistic processing depends on the definition of holistic processing. Here, we use the term to refer to global template matching, adopting the definition by Hummel and colleagues, as the current approach was motivated by Hummel's (2001) hybrid model. On other accounts, splitting an object does not necessarily abolish all holistic processing, because certain feature configurations are preserved in split images.

On the basis of recent studies showing that priming shortens suppression times (Costello et al., 2009; Lupyan & Ward, 2013), we expected primed objects, relative to unprimed objects, to have an advantage in gaining access to awareness. Moreover, if this beneficial effect of prior information on visual awareness depended on the observers' top-down set (Gayet et al.,

2013) and attentional focus, we would expect stronger priming effects from spatially attended objects. Finally, if similar mechanisms supported the detection and the recognition of objects, we would expect priming from intact objects irrespective of whether they are attended or unattended. In contrast, split objects should produce priming (albeit less than intact primes) only when attended (Thoma et al., 2004), reflecting the attentional demands of analytic, part-based object processing as opposed to automatic but view-dependent processing (Hummel, 2001).

Method

Participants

Thirty volunteers (22 female, age range 19–29 years, mean age 22.5 years, $SD = 2.7$ years), all students recruited through the Charité University Hospital subject pool, participated in the experiment for payment. All participants reported normal or corrected-to-normal vision and were naive as to the purpose of the experiment. The study adhered to the Declaration of Helsinki and was approved by the ethics committee of Humboldt University (Berlin).

Apparatus and stimuli

Stimuli were presented on a 19-in. CRT screen (1024 $\times$ 768 pixel resolution, 60-Hz refresh rate) that observers viewed from a distance of 50 cm through a custom-built mirror stereoscope, with their heads stabilized by a head-and-chin rest. Throughout the experiment, two frames (12.3° $\times$ 12.3°) with borders (width 0.5°) consisting of random noise pixels (to support binocular fusion) were presented side by side on the black screen (distance between the centers of the two frames 10.6°), such that one frame was visible to each eye. These frames enclosed a uniform white background (11.3° $\times$ 11.3°) against which all stimuli were presented. Visual stimuli were presented with Matlab (The MathWorks, Natick, MA) using the Cogent 2000 toolbox functions (http://www.vislab.ucl.ac.uk/cogent.php).

A total of 264 photo-realistic images of unique nameable everyday objects were selected from three different data bases (Brodeur, Dionne-Dostie, Montreuil, & Lepage, 2010; Tarr, 2015; Viggiano, Vannucci, & Righi, 2004). Objects were converted to grayscale, fit to a square (3.3° $\times$ 3.3°, by scaling the longer axis), and normalized for average luminance and root mean square (RMS) contrast. We created split versions of these intact objects by cutting them along the vertical midline and swapping these halves. The resulting split objects appeared to be cut in two halves (see Figure 1a). Thus, while intact and split images contained identical pixels, splitting distorted the holistic properties, not the part-based aspects of the objects (Thoma et al., 2004).

A subset of 120 of the intact objects served as targets in b-CFS. Targets had different relations to the preceding critical primes, depending on the experimental condition (see below). Of these 120 target objects, 85 depicted nonliving objects, and 35 living objects. The remaining 144 objects (107 nonliving, 37 living) were used as fillers in the prime displays. To induce interocular suppression, we created high-contrast, contour-rich CFS masks (4.8° $\times$ 4.8°) consisting of randomly arranged white, black, and gray circles (diameter 0.2°–1.0°).

Procedure

The temporal sequence of a trial is illustrated in Figure 1a. Trials began with a 1-s presentation of the blank frames only, followed by the priming period in which all stimuli were presented binocularly (i.e., all stimuli were presented to both eyes, not inducing interocular suppression), which was followed by the b-CFS period where participants detected objects under interocular suppression (Figure 1b). During the priming period, a small black fixation dot was presented in the center of the frames. During the b-CFS period, a white fixation cross with a black outline was centered in the frames. Participants were instructed to maintain stable fixation during both periods. In the priming period all stimuli were centered at 3.1° left or right of fixation, whereas in the b-CFS period all stimuli were centered at 3.1° above or below fixation.

The priming period began with a 2-s presentation of the frames and the fixation dot only. Next, a black attentional cueing frame (4.8° $\times$ 4.8°) was presented either to the left or to the right of fixation. After 66 ms, two object stimuli were presented simultaneously for 150 ms to the left and to the right of fixation, one of them within the cueing frame. Depending on the experimental condition, these primes could be both intact, both split, or one of each. Participants were instructed to covertly name the object shown in the cueing frame and to press the keyboard key "Q" with their left hand to indicate when they successfully identified the attended object. A backward mask (4.8° $\times$ 4.8°) consisting of random noise pixels shown for 450 ms followed the presentation of each of the two prime images. Finally, the priming period ended with a 2-s presentation of the frames and the fixation dot only to give participants sufficient time for covert naming and for pressing the corresponding key. The proportion of trials with a button press reflecting successful identification of the attended prime was high for intact objects ($M = 92.1\%$, $SD = 5.4\%$), and significantly lower for split objects ($M = 71.6\%$, $SD = 15.1\%$), $t(29) = 9.77$, $p < 0.001$. This covert naming task was implemented to ensure that participants attended the cued object, tried to identify it, and ignored the other prime. Naming tasks also have previously been found to be more sensitive to view changes in priming paradigms compared to other types of tasks (Biederman & Cooper, 1991; Bruce, Carson, Burton, & Ellis, 2000). Because the decision to indicate successful object identification and to press the corresponding key is strongly dependent on the observer's criterion, in our main analysis we did not exclude trials without a button press, but included all trials in the computation of suppression times. For consistency with previous research using naming tasks (Thoma & Davidoff, 2006; Thoma et al., 2007; Thoma et al., 2004) we conducted an auxiliary analysis in which trials without a button press during the prime period were excluded.

In the directly succeeding b-CFS period, an intact target object centered above or below the fixation cross was gradually introduced to the participant's dominant eye. Simultaneously, CFS masks updated at 10 Hz were centered above and below the fixation cross in the frame presented to the participant's nondominant eye. The dominant eye was considered as the eye with shorter mean suppression times in a simple b-CFS experiment at the beginning of the experimental session (Yang, Blake, & McDonald, 2010; 17 of our 30 participants were right-eye dominant according to this method). To avoid abrupt transients, over the first 500 ms of the b-CFS period, the target contrast was linearly increased from zero to its original contrast while the target luminance was linearly reduced from full white (as the background) to its original luminance. Starting 2 s after the beginning of the b-CFS period, the contrast of the CFS masks was linearly reduced to zero over a period of 7 s. Participants used their right hand to press the up and down arrow keys on the keyboard to localize the position of the initially invisible target. They were asked to respond as quickly and accurately as possible as soon as they detected an object or any part of it either on the lower or upper half of the screen. The b-CFS period ended either upon response or after a maximum duration of 10 s.

Experimental conditions and design

The assignment of the stimuli to the different experimental conditions was counterbalanced across participants by placing the 120 target objects in five different clusters, such that each target object appeared in the five conditions equally often across participants. Experimental conditions differed regarding the relation between one of the two objects in the priming period, that is, the critical prime, and the intact target object presented in the b-CFS period. The conditions were (a) attended-intact (the target object was attended in the prime display), (b) attended-split (the target object was attended in the prime display, but presented as its split version), (c) unattended-intact (the target object was ignored in the prime display), (d) unattended-split (the target object was ignored in the prime display, and presented as its split version), and (e) unprimed (the target object was not presented in the prime display).

Participants completed two experimental blocks with 120 trials each (within a block, there was an additional obligatory break after 60 trials), in which each of the 120 target objects was presented once. Within a block, there were 24 trials per condition, and an equal number of trials with the precue presented to the left or right of fixation and with the target appearing in the upper and lower position. The critical prime was chosen according to the counterbalancing across participants described above, and the other object in the prime display was sampled without replacement from the 144 fillers. This filler object was intact in half of the trials and split in the other half. In the unprimed condition, both objects in the prime displays were fillers (50% intact, 50% split). Trial order was randomized. Before starting the experiment proper, there were 10 practice trials using another set of object stimuli.

Analysis

For the main analysis, trials with incorrect target localization responses, trials without a localization response, and trials with localization responses shorter than 200 ms were excluded from the analyses of suppression times (mean percentage of excluded trials 1.1%, $SD = 1.5\%$). For easy eyeballing of the overall suppression times in seconds, Figure 2a shows mean suppression times for the five experimental conditions. For all statistical analyses, suppression times were log-transformed (see Figure 2b) to account for their positive skew. An auxiliary analysis was carried out in a fashion analogous to previous work using naming tasks (Thoma & Davidoff, 2006; Thoma et al., 2007; Thoma et al., 2004). Following these previous studies, one participant who was not a German native speaker was excluded and trials in which participants did not indicate having identified the prime (mean percentage 17.6%, $SD = 9.4\%$) were also excluded. Also for this auxiliary analysis suppression times were log-transformed.

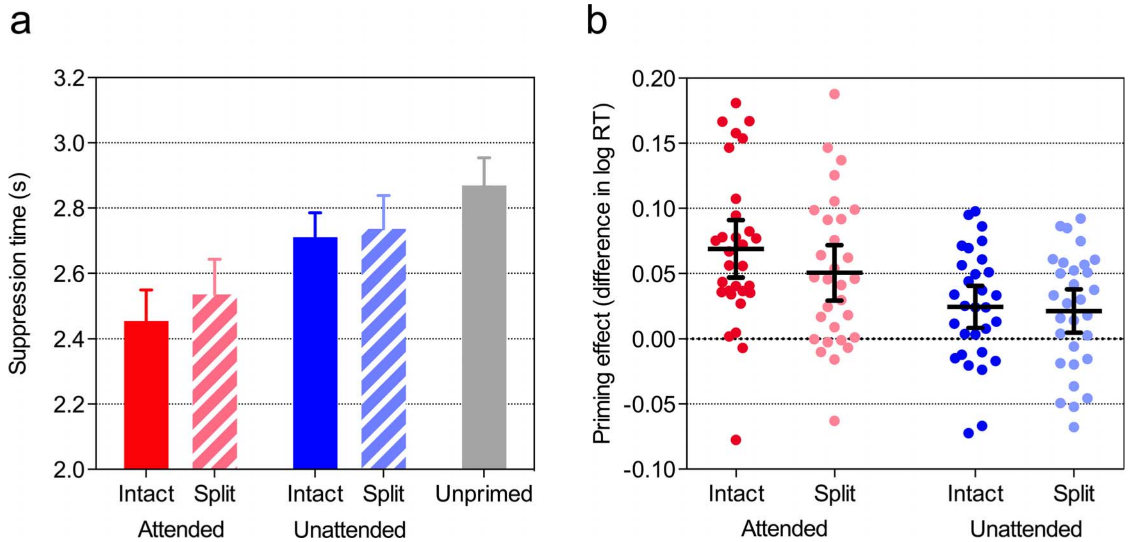

Figure 2. (a) Mean suppression times in seconds for all five conditions. Error bars represent 95% CIs for within-subjects designs. (b) Priming effects, that is, the differences in log-transformed suppression times between the unprimed condition and the four priming conditions. Circles represent data from individual participants, horizontal bars show means, and vertical error bars show 95% CIs.

Results

Priming effects were computed as the differences in log-transformed suppression times between the unprimed baseline condition and the four priming conditions. To test our hypotheses, we ran two types of analyses. First, to test whether these priming effects were significantly greater than zero, one-tailed one-sample t tests were conducted separately for each priming condition. As can be seen from Figure 2b, in the main analysis the priming effects were significant for attended-intact, $t(29) = 6.40$, $p < 0.001$, $d = 1.17$; for attended-split, $t(29) = 4.90$, $p < 0.001$, $d = 0.89$; for unattended-intact, $t(29) = 3.10$, $p = 0.002$, $d = 0.57$; and for unattended-split, $t(29) = 2.63$, $p = 0.007$, $d = 0.48$. Thus, the presentation of a visible prime that was related to the target presented under CFS resulted in shorter suppression times relative to the unprimed condition. This priming effect on the conscious detection of intact objects occurred even when the primes were split and unattended.

The auxiliary analysis on the trials with successful prime identification analysis yielded a similar pattern of results. One-tailed one-sample t tests revealed significant priming effects for attended-intact, $t(28) = 5.95$, $p < 0.001$, $d = 1.10$; for attended-split, $t(28) = 5.40$, $p < 0.001$, $d = 1.00$; for unattended-intact, $t(28) = 2.89$, $p = 0.004$, $d = 0.54$; and for unattended-split, $t(28) = 2.63$, $p = 0.033$, $d = 0.36$.

Second, we analyzed these priming effects using a two-way repeated-measures ANOVA with the factors prime attention (attended, unattended) and prime intactness (intact, split). Only the main effect of attention was significant, $F(1, 29) = 21.07$, $p < 0.001$, $\eta_p^2 = 0.42$, with larger priming effects for attended primes (Figure 2). The main effect of prime intactness did not reach significance, $F(1, 29) = 2.34$, $p = 0.137$, $\eta_p^2 = 0.08$, meaning that intact and split primes were similarly effective in facilitating access to awareness for intact target objects under CFS. The interaction between attention and intactness did not approach significance, $F(1, 29) = 1.55$, $p = 0.223$, $\eta_p^2 = 0.05$, indicating that attention enhanced priming effects from intact and split objects to a similar extent.

The auxiliary analysis, including only the trials with successful prime identification, confirmed these findings. There was only a significant main effect of attention, $F(1, 28) = 26.54$, $p < 0.001$, $\eta_p^2 = 0.49$, but no significant main effect of prime intactness, $F(1, 28) = 1.04$, $p = 0.316$, $\eta_p^2 = 0.04$, and no significant interaction, $F(1, 28) = 0.27$, $p = 0.610$, $\eta_p^2 = 0.01$.

Discussion

The current study was designed to test whether high-level object representations facilitate the simple detection of an object and whether object detection relies on perceptual mechanisms similar to those previously found to underlie object recognition. For this, we measured priming effects on the conscious detection of objects using a b-CFS procedure. Relative to an unprimed baseline condition, suppression times for objects that were preceded by a related prime were significantly shorter. The general advantage of primed stimuli compared to nonprimed stimuli in overcoming

CFS is in line with recent studies that found shorter suppression times for primed stimuli (Costello et al., 2009; Lupyan & Ward, 2013). To establish what kind of object representation could mediate such facilitation, we manipulated visual attention and object intactness, that is, the holistic configuration of an object, according to the hybrid model by Hummel (2001). When an object received spatial attention, it greatly enhanced the priming effect measured as facilitated access to awareness. The strong effect of attention on priming is consistent with work showing that the beneficial effect of prior target-related information on visual awareness is not only driven by passive, bottom-up stimulus processing, but also strongly modulated by the observer's top-down set (Gayet et al., 2013). Interestingly, however, compared to the unprimed baseline, even unattended primes reliably boosted access to awareness. These reliable priming effects for unattended primes indicate that object detection does not necessarily involve high-level part-based object processing, as such analytic object representations require attention to bind parts into coherent objects (Hummel & Biederman, 1992). Moreover, priming effects did not depend on object intactness, neither for attended nor for unattended primes. That is, awareness of a target presented in the common intact view was similarly facilitated by the same intact prime and by a horizontally split prime. Thus, the part–whole configuration of the prime, which is partially distorted in split objects, is not crucial for priming of object detection to occur, suggesting that object detection is less dependent on holistic representations than object identification. Together, these findings are further evidence that the processes leading to detection of objects are at least partly different from those needed for object recognition (Mack & Palmeri, 2010). Moreover, our data indicate that the simple detection of objects relies on representations of object features rather than analytic or holistic high-level representations.

The approach of the current study was also motivated by the hybrid model of object recognition (Hummel, 2001) according to which the recognition of attended objects involves both analytic and holistic representations, whereas the recognition of unattended objects involves holistic representations only. This central tenet of the hybrid theory is supported by evidence from studies on priming of object recognition that used the same attention and part-whole configuration manipulations as in the present experiment (Thoma & Henson, 2011; Thoma et al., 2004). Because splitting at least partially disrupts the holistic match between the prime and the target, split primes are thought to facilitate target recognition only through an analytic, part-based representation. Indeed, for object recognition, priming effects from intact objects are larger than from split objects, indicating an additional contribution from holistic object representations (Thoma et al., 2004). In the present object detection experiment, by contrast, access to awareness was facilitated to a similar extent by intact and split primes. The absence of an advantage for intact primes suggests that holistic object processing (Bülthoff & Edelman, 1992; Edelman & Intrator, 2003; Tarr, 1995) that is partially disrupted by split images plays little role in the initial detection of an object. This is consistent with evidence from b-CFS studies showing that stimulus inversion (i.e., rotating the image by 180°, thereby distorting the spatial configuration) has little influence on the detection of familiar objects from a wide range of categories (with the exception of human faces and bodies, Stein et al., 2012, Zhou et al., 2010). Thus, the perceptual mechanisms underlying the detection of many familiar objects seem fairly robust to changes in part–whole configuration.

In principle, these findings could well be explained by analytic, part-based object representations that are robust to view changes (Biederman, 1987; Hummel & Biederman, 1992). However, the literature on object recognition suggests that such analytic representations require attention, because split objects (Thoma et al., 2004) as well as rotated images (Thoma et al., 2007) prime the recognition of intact targets only when they are attended. In fact, in the present experiment the priming effects from attended objects were considerably larger than from unattended objects. Nevertheless, object representations based on (attention-dependent) structural descriptions cannot be the only mechanism involved in object detection, as we found that even unattended split objects facilitated access to awareness for a related intact target. Although this attention manipulation has been shown to successfully draw attentional resources to the spatially cued prime and away from the unattended, ignored prime (e.g., Thoma et al., 2004) this approach does not necessarily allow us to fully exclude occasional "slippage" of attention to the ignored prime. Previous studies sought to account for a possible influence of slippage. For example, the study by Thoma and Davidoff (2006, experiment 1) used catch trials in which subjects were asked to name the unattended prime: None of the 26 observers could correctly name the unattended prime. Previously, Stankiewicz, Hummel, and Cooper (1998) showed with this paradigm that unattended objects prime themselves in a probe display when shown in the same orientation but not in a mirror-image version of itself. This priming result could not be expected if attentional slippage was assumed. In addition, in an fMRI study using the same attentional and view (splitting) manipulation Thoma and Henson (2011) found no significant repetition suppression effects for unattended objects in object responsive lateral occipital cortex. We thus deem it highly unlikely that occasional slippage of attention in prime trials to the unattended object can account for our data.

Thus, attention-dependent analytic object representations are unlikely to fully account for priming of object detection. How, then, could we characterize the perceptual mechanism underlying the initial detection of objects? One possibility is that priming from unattended objects relies on a representation of a "shapeless bundle of features" (Wolfe & Bennett, 1997). Indeed, Wolfe and Horowitz (2004) suggest that a number of features may be processed in parallel and pre-attentively in order to guide attention to then allow binding and recognition. An attention-related amplification of such simple representations of object features may account for the additive effect of attention observed in the present experiments. Whereas this simple feature representation seems sufficient for the conscious detection of an object in the visual field, identification, naming, and more elaborate object processing demand higher-level object representations.

We studied these perceptual mechanisms underlying conscious object detection by recording the duration of perceptual suppression under CFS. While we here interpret differences in suppression times simply as reflecting differences in detection sensitivity, a number of previous studies have implemented the b-CFS paradigm to study unconscious processing under interocular suppression (e.g., Costello et al., 2009; Jiang et al., 2007; Stein, Senju, Peelen, & Sterzer, 2011; Zhou et al., 2010). In several studies, unconscious processing was inferred when a binocular control condition not involving interocular suppression yielded smaller detection differences than the b-CFS condition. We did not include such a control condition, because the logic of relying on a control condition to infer unconscious processing in the b-CFS condition has recently been challenged on empirical and theoretical grounds (Stein, Hebart, & Sterzer, 2011; Stein & Sterzer, 2014). Nevertheless, mere differences in conscious detection could, in principle, be regarded as evidence that stimuli were processed differentially before they were detected, that is, unconsciously (Dijksterhuis & Aarts, 2003; Gaillard et al., 2006). While this inferential step has some face validity, it is neither commonly made nor generally accepted in the literature (e.g., Labiouse, 2004). Only paradigms in which stimuli are rendered permanently invisible are currently considered as providing unequivocal evidence for unconscious processing (e.g., Sterzer, Stein, Ludwig, Rothkirch, & Hesselmann, 2014). We therefore take our findings simply as evidence for the modulation of detection mechanisms by the preceding primes.

One important challenge for future work is to test to which extent findings obtained with the laboratory technique of CFS generalize to object detection under real-world conditions. For the purpose of the present study, we decided to implement CFS because previous studies have demonstrated that the b-CFS paradigm represents a particularly sensitive measure of the influence of priming and of configural or holistic stimulus properties on visual detection. For example, one of the most robust b-CFS findings is that upright faces and bodies break suppression more quickly than the same stimuli presented in inverted orientations, despite all physical stimulus features being identical (Heyman & Moors, 2014; Jiang et al., 2007; Stein, End, & Sterzer, 2014; Stein, Hebart, & Sterzer, 2011; Stein, Peelen, & Sterzer, 2011; Stein et al., 2012; Yang, Zald, & Blake, 2007; Zhou et al., 2010). At the same time, recent studies that used both b-CFS and other detection paradigms to study object detection have demonstrated comparable effects with b-CFS and with attentional blink and standard masking paradigms (Gobbini et al., 2013; Stein, Seymour, Hebart, & Sterzer, 2014). We thus believe that the present results likely generalize to other psychophysical techniques for studying object detection. However, findings obtained exclusively with these well-controlled laboratory tools do not necessarily fully account for real-world world perception. A promising avenue for future studies thus consists in extending the present approach to real-world stimuli, for example by studying top-down and priming influences on object detection in natural scenes (e.g., Reeder & Peelen, 2013; for a review, see Peelen & Kastner, 2014).

In summary, the initial detection of objects can be strongly influenced by prior visual information on the object, and this influence does not seem to require high-level analytic or holistic representations of the primed object, and most likely not even representations of 3-D parts. Whatever the exact nature of the features driving the priming for detection, it is intriguing that even unattended objects induced significant priming. Apart from providing insights into the format of visual object representations mediating simple detection, priming effects from unattended objects also rule out that the effects obtained with the present paradigm were due only to conceptual or name priming, which most likely contributed to priming from spatially attended objects. It is unlikely, however, that covert naming can fully account for priming from attended objects. Even for object-naming tasks, the dominant mechanism underlying the priming effect has been shown to be perceptual in nature, whereas name priming exhibited only a comparably small effect (Thoma et al., 2004). Interestingly, previous work on object recognition using a similar priming paradigm has also shown that participants are not conscious of the identity of unattended objects in the prime display (Thoma & Davidoff, 2006). This raises the possibility that feature-based object representations that govern visual priming of object detection do not need to make contact with higher-level processes involved in object recognition and naming. Future work could directly test whether these priming effects can be obtained in the complete absence of prime awareness (e.g., Barbot & Kouider, 2012).

In conclusion, the current data show for the first time that spatially unattended primes can facilitate awareness of objects under CFS. In addition, our findings indicate that the processes underlying priming of object detection are different from those for object recognition, as the former are equivalent for non-holistic part configurations. Rather than relying on complex holistic and part-based object representations, the initial detection of an object seems to involve representations of basic object features that can be established pre-attentively but are strongly boosted by voluntary spatial attention. Future research will have to establish in more detail whether the locus of the priming resides in the representation of simple low-level features, the surfaces of an object, or its volumetric parts (e.g., Hummel & Biederman, 1992).

Keywords: object perception, conscious detection, visual awareness, continuous flash suppression, priming, attention

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