Perceptual benefits of objecthood

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Object-based attention facilitates the processing of features that form the object. Two hypotheses are conceivable for how object-based attention is deployed to an object's features: first, the object is attended by selecting its features; alternatively, a configuration of features as such is attended by selecting the object representation they form. Only for the latter alternative, the perception of a feature configuration as entity ("objecthood") is a necessary condition for object-based attention. Disentangling the two alternatives requires the comparison of identical feature configurations that induce the perception of an object in one condition ("bound") and do not do so in another condition ("unbound"). We used an ambiguous stimulus, whose percept spontaneously switches between bound and unbound, while the stimulus itself remains unchanged. We tested discrimination on the boundary of the diamond as well as detection of probes inside and outside the diamond. We found discrimination performance to be increased if features were perceptually bound into an object. Furthermore, detection performance was higher within and lower outside the bound object as compared to the unbound configuration. Consequently, the facilitation of processing by object-based attention requires objecthood, that is, a unified internal representation of an "object"—not a mere collection of features.

Keywords: attention, detection/discrimination, object recognition, perceptual organization, visual cognition

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Introduction

The question "what is an object?" has attracted widespread interest. Two main views on how objects are formed exist: a "bottom-up" local processing of Gestalt cues and a more traditional Gestalt "top-down" global organization (e.g., Treisman & Gelade, 1980). The bottom-up approach suggests that the brain uses specific Gestalt cues (Brunswik & Kamiya, 1953) to form a holistic object representation from a constellation of parts. From this point of view, the representation of an object is formed if the right combination and layout of features is chosen. The top-down approach proposes that something becomes an object after a higher level representation is formed (e.g., Kahneman, Treisman, & Gibbs, 1992). Specific combinations of features may activate such a representation, but the representation itself is needed to bind features into a single object. These views are not mutually exclusive. Indeed, more recent findings suggest that both early feature integration and higher stages play a crucial role in the processing of objects (e.g., Altmann, Bülthoff, & Kourtzi, 2003; Kourtzi, Tolias, Altmann, Augath, & Logothetis, 2003). Nonetheless, experimental studies have not yet fully disentangled effects of object representations from feature configurations. These disparate views on object integration call for resolution. Does attention manifest itself along feature configurations or is it deployed to objects (e.g., Crundall, Dewhurst, & Underwood, 2008; Houtkamp, Spekreijse, & Roelfsema, 2003; Roelfsema, Houtkamp, & Korjoukov, 2010)?

How can effects of objects be disentangled from the features they are made of? In the realm of attention, the question of how objects guide attention allocation has been the topic of many studies (e.g., Duncan, 1984; Kahneman et al., 1992; Watson & Kramer, 1999). Evidence in favor of object-based attention mainly demonstrates a benefit for responses when attention has to switch within a single object opposing to between multiple objects (e.g., Egly, Driver, & Rafal, 1994; Moore, Yantis, & Vaughan, 1998). Several other paradigms, including inattentional blindness (Moore & Egeth, 1997) and visual search (Enns & Rensink, 1991), are similarly affected by object-based effects. In principle, such results could still be linked to feature constellations rather than being specific to "objecthood." Even if features are bound to objects pre-attentively,

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a subjective impression of objecthood might or might not be required for "object-based" benefits. The notion of object-based attention has, therefore, been challenged. In addition, the lack of a precise definition of an "object" (Scholl, 2001) makes studying objects independent of the constituting features challenging. This definition problem has thwarted a sequence of studies from making solid statements about how attention is allocated to objects and what underlies object-based attention effect. Studies that evaluated performance facilitation of attending to an "object" have, thus, experienced difficulty with the disentanglement of feature cues that constitute the object and the cognitive concept and representation of an "object." Indeed, subjective formations of objects are highly associated with, and arguably defined by, feature cues (i.e., Gestalt) like contour and form. Several attempts have been made to circumvent this problem: studies have avoided crafting objects with stimulus manipulations but instead control an observers' perceptual interpretation of features as an object (e.g., Baylis & Driver, 1993). However, eventually all reported attentional object-based benefits could be explained by specific features such as contour (Gibson, 1994), closure (Marino & Scholl, 2005), line collinearity (Avrahami, 1999; Crundall, Cole, & Galpin, 2007; Kimchi, Yeshurun, & Cohen-Savransky, 2007), and other Gestalt-like principles (Feldman, 2007). These studies opened up the possibility that cues such as figure–ground organization, closure, and collinearity facilitate performance and underlie the within-object advantage. From this point of view, it may be that a collection of organized stimulus features instead of a unique object representation is what derives "object-based" benefits.

Ambiguous stimuli can disentangle the subjective impression of objecthood from the physical constellation of object features. Using fMRI, Murray, Kersten, Olshausen, Schrater, and Woods (2002) demonstrated that ambiguous stimuli are useful as a tool for studying object processing in the absence of confounding effects related to feature constellations (see also Andrews, Schluppeck, Homfray, Matthews, & Blakemore, 2002; Fang, Kersten, & Murray, 2008). The stimulus they used was an ambiguously moving diamond that induces two interpretations: either a bound percept of a single object or an unbound percept of multiple objects (Lorenceau & Shiffrar, 1992). The diamond's configuration can lead to the percept (i.e., a subjective impression) of a single diamond moving sideways behind three bars (Figure 1a) or as multiple apertures that independently move up and down (Figure 1b), while the stimulus is kept constant. Independent of physical changes, attention may be either spatially divided over the four apertures of the ambiguous diamond or allocated to the object as a whole. The ambiguous diamond is an ideal tool to address the issue of whether object-based attention effects are still present if the perceptual differentiation between objects is only caused by an internal subjective interpretation. Thus, by using this ambiguous stimulus, the problem of defining an object is removed because the observers' internal percept defines the objects and, in contrast to Baylis and Driver's design (1993), the attended objects will always constitute of exactly the same physical properties.

In the present study, we use the ambiguous diamond to test whether a single or multi-object percept has an effect on discrimination and detection performance. In other words, we address the question as to whether the perceptual integration (i.e., binding) of the independent moving apertures into a single object (i.e., a diamond) will facilitate its processing. We will show that subjective impression of a single bound object improves observers' performance in both discriminating and detecting physical changes of the object as compared to the situation in which the percept constitutes of multiple unbound (i.e., non-integrated) objects. We further will show that the processing on an object itself gets facilitated while processing on regions outside the object get suppressed. Our experimental results are strong evidence for the notion that Gestalt cues are not solely responsible for object-based effects and that the formation of a unique representation of an object is sufficient to enable attention to be allocated to an object.

Methods

Observers

Author M.N. and 9 naive observers (4 male and 6 female students in the age range of 20–30) participated in each experiment. In each experiment, two observers were excluded from analysis for reasons provided below. Data of both experiments were, therefore, based on 8 observers. Observers had normal or corrected-to-normal vision. Each observer gave written informed consent before participation; all procedures adhered to national standards on experiments with human observers and with the Declaration of Helsinki.

Stimuli

The stimulus used in both experiments was a 10-deg-wide square rotated 45 deg (i.e., a diamond) moving sideways behind three vertical bars (see Movie 1 in the Supplementary material). The movement of the diamond induces an ambiguous perceptual state consisting of either a percept of a single object oscillating side to side horizontally (Figure 1a) or multiple apertures moving up and down (Figure 1b). As differentiation between the two percepts includes the process of binding features into an object, we will refer to the single-object percept as *bound* and the multi-object percept as *unbound*. The visibility (i.e., dominance) of these percepts alternates over time, each percept being dominant for several seconds until

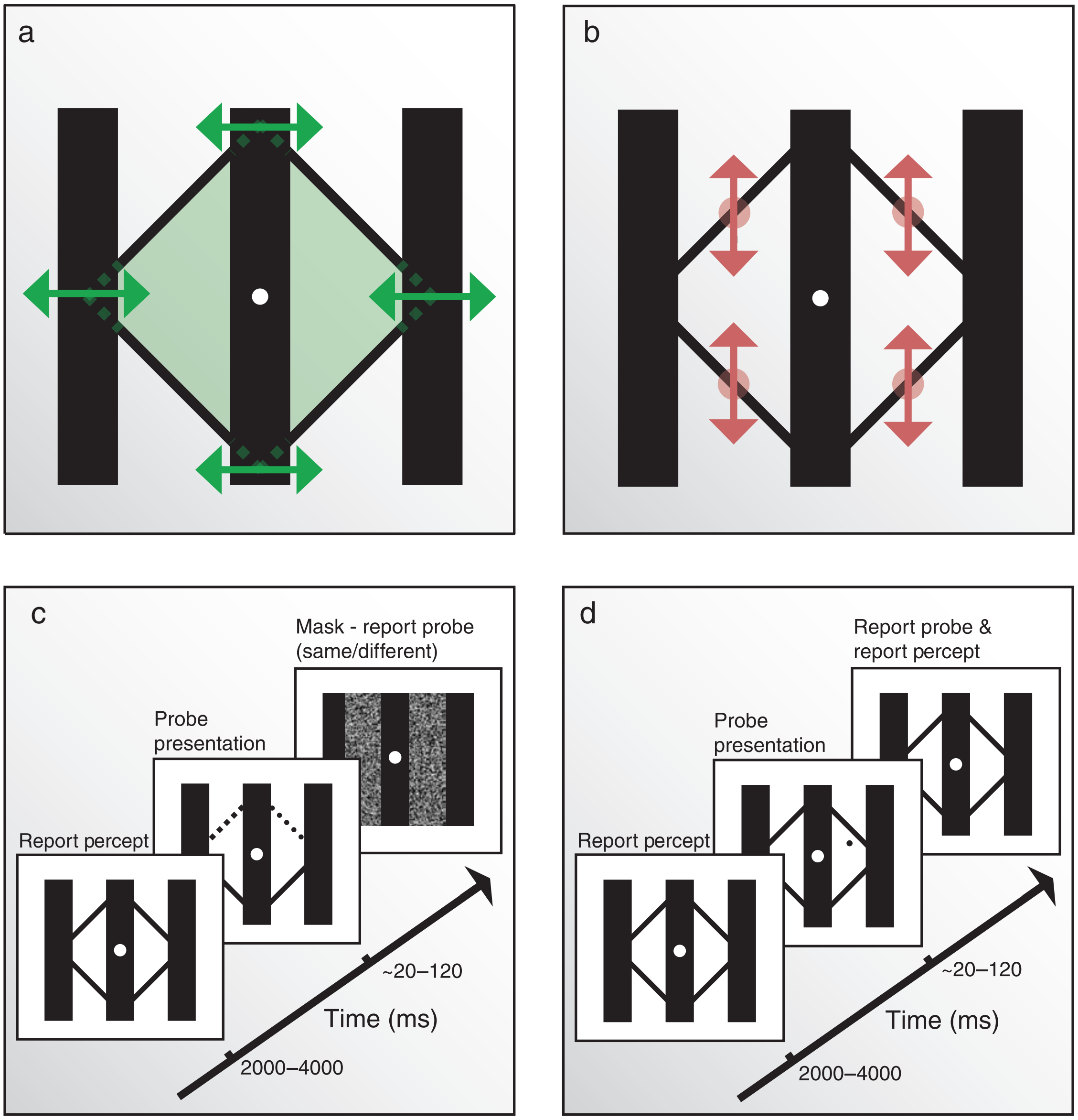

Figure 1. Stimuli. The ambiguous moving diamond induces two distinct percepts (colors and arrows are for visualization only and not present in the actual stimulus): (a) a single *bound* object (green surface and arrows) coherently moving sideways or (b) multiple *unbound* objects (red arrows) making oscillating movements up and down. To experience the perceptual ambiguity induced by this stimulus, see movies in the Supplementary material: Movie 1 for the ambiguous stimulus and Movie 2 for disambiguation by luminance changes. (c) Procedure during discrimination Experiment 1: Observers indicated the dominant percept; 2000–4000 ms later, two apertures were briefly changed to either a dashed or dotted line, and the probes were masked by random noise pattern after 20–120 ms (the SOA depended on the observers' performance threshold). Probes were either *different* (i.e., one dashed and the other dotted) or the *same* (i.e., both dashed or both dotted). (d) Procedure during detection Experiment 2: Observers continuously indicated the dominant percept, and every 2000–4000 ms, a small probe was presented for 20–120 ms inside or outside the diamond. Black and white values in this figure are inversed, that is, the background and fixation dot were actually black and the diamond lines were white during the experiment.

the other percept takes over. To induce ambiguity, the diamond had a 1-deg sinusoidal movement pattern between outer left and right borders of the occluding bars. These bars ensured the invisibility of the diamond's corners, an essential property for the stimulus' ambiguity. A 0.1-deg-wide fixation dot was presented on the center of the screen. Mean luminance of the stimulus was 33.9 cd/m^2.

Apparatus

Stimuli were generated using Matlab (Mathworks, Natick, MA) with Psychophysics toolbox (Brainard, 1997; Pelli, 1997). Stimuli were presented by an Optiplex Dell computer and a 21-inch EIZO Flexscan monitor on a black background with 1152 × 864 pixels at 100-Hz refresh rate.

Head position was stabilized using chin and forehead rests that assured a steady viewing distance of 73 cm.

Procedure

Observers performed two experiments on separate days. Experiments consisted either of a discrimination (Figure 1c) or detection task (Figure 1d) in which the performance during both the bound and unbound percepts was measured. Observers were familiarized with the stimulus and setup before the actual experiment. During the experiment, observers had to fixate and indicate the dominant percept by holding down one of two buttons.

Experiment 1—Discrimination

The first experiment was designed to test whether perceptual binding of multiple apertures (i.e., the diamond's borders) into a single object facilitated discrimination performance. In each trial of Experiment 1, between 2 and 4 s after observers started reporting their percept, two adjacent borders of the diamond were briefly (see below for timing) changed to either a dotted or dashed pattern (Figure 1c). This probe was followed by a random noise mask to prevent image aftereffects. After mask onset, observers stopped reporting their dominant percept and indicated using two buttons whether both borders were the *same* (i.e., both dotted or both dashed) or *different* (i.e., one dotted and the other dashed). Observers were allowed to take all the time they needed to make their decision. The next trial only started after the observer's response and an experiment consisted of a total of 300 trials.

Experiment 2—Detection

In the second experiment, we tested whether detection performance in and around the objects was modulated by perceptual binding. Observers were briefly presented (20 ms) with 0.1-deg-wide Gabor-shaped probes in and around the diamond while they—at the same time—reported their dominant percept (Figure 1d). Every time observers had detected a probe, they reported this with an additional button. A total number of 1200 probes were shown during the experiment. The time between probe onsets was 2 to 4 s and probes could be shown anywhere in and around the stimulus within an annulus-shaped region with inner and outer radii of 5 and 15 deg, respectively. Trials in which reaction times were faster than 200 ms or slower than 2000 ms were excluded from analysis (0.7% of all trials).

Individual adjustment of perceptual dominance

Since perceptual dominance can vary over the course of the experiment and is influenced by interruptions of stimulus presentation (e.g., Orbach, Ehrlich, & Vainstein, 1963), and biases in dominance (i.e., one percept is preferred over the other) could, in principle, be directly related to detection or discrimination performance, we aimed at about equal probability in dominance for both percepts (i.e., *bound* and *unbound*). This perceptual balance was created by altering the luminance of the occluding bars: A higher luminance biases dominance toward the *bound* percept and a lower luminance toward the *unbound* percept (see Movie 2 in the Supplementary material that demonstrates that dominance of the percept depends on the luminance of the occluding bars). We adjusted this luminance for each observer in a short experiment preceding each of the main experiments. For 5 min, observers only indicated the dominant percept and a QUEST procedure (Watson & Pelli, 1983) resulted in a luminance value for the occluding bars at which the observer's perceptual dominance between the percepts was balanced. The luminance corresponding to equality spanned a wide range across observers, ranging from 0.11 to 6.77 cd/m^2 (Median: 0.40 cd/m^2). In the test preceding Experiment 1, two observers showed a substantial bias in dominance toward the *unbound* interpretation (73% and 80% dominance) and were thus removed from analysis. In the test preceding Experiment 2, one observer failed to balance both percepts (70% dominance for unbound) and was excluded from analysis.

Individual adjustment of performance

We prevented floor and ceiling effects in discrimination and detection performance by having observers perform a 5-min version of the main experiment in which a QUEST procedure searched for the 75% correct performance threshold. Discrimination performance was adjusted by varying the time between probe and mask onsets (Stimulus Onset Asynchrony, SOA): shortening the SOA resulted in a performance decrease. The mean SOA over all observers for a 75% performance was 63 ms (*SD*: 34 ms). Detection performance was manipulated by adjusting the probe luminance: lowering luminance resulted in a decrease in performance (Mean: 0.65, *SD*: 0.08).

To make sure that observers did not exchange response buttons, and stayed actively involved with the task, we added catch trials in each experiment. During these trials, the occluding bars suddenly changed to white (luminance: 33.9 cd/m^2), where it was expected that the observer would always report the *bound* percept. One observer did not report this *bound* percept in 3 out of 4 cases in Experiment 2, which indicates that this observer might have accidentally switched buttons. This observer was excluded from the analysis of Experiment 2.

Analysis

First, we computed *performance* (number of trials in which probes were correctly discriminated or detected

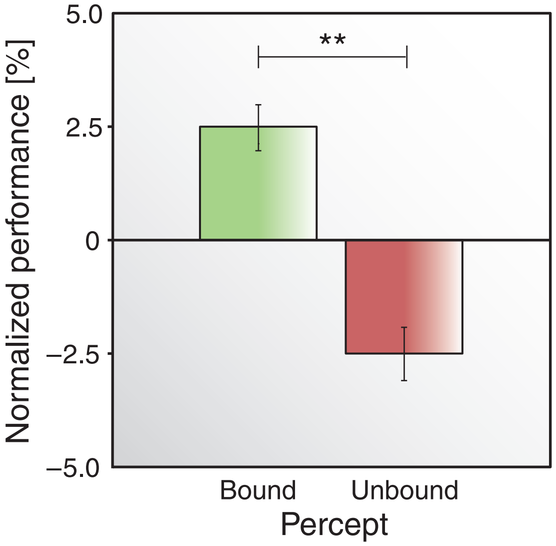

Figure 2. Performance in Experiment 1. Mean and standard errors of discrimination performance per percept. Discrimination performance was significantly better for the bound percept as compared to the unbound percept.

divided by the total number of trials) and *dominance* (number of trials in which a percept was dominant at the time of probe onset divided by the total number of trials). For both experiments, trials in which no percept was reported were excluded from analysis. Differences in performance between conditions were evaluated and statistically tested using paired *t*-tests.

Results

Experiment 1—Object border discrimination

We first examined how observers' subjective impressions of the ambiguous diamond affected dominance and discrimination performance. The analysis showed that discrimination performance depended significantly on whether the bound or unbound percept was dominant at the moment of probe onset (Figure 2a). Observers performed significantly better at discriminating features across the stimulus for the bound percept as compared to the unbound percept (Difference: 5%; $t(7) = 3.98$, $p < 0.01$). Dominance of both percepts was balanced well across observers (mean unbound: 54%, *SD*: 9%; $t(7) = 1.20$, $p > 0.25$). Response times were not significantly different between percepts (mean bound: 1.64 s, *SD*: 0.43; mean unbound: 1.59 s, *SD*: 0.38 s; $t(7) = 1.55$, $p > 0.10$). Although there was an overall selection bias of *same* over *different* probes ($t(7) = 6.08$, $p < 0.001$), we found no further response biases between the percepts ($t(7) = 0.58$, $p > 0.50$). In conclusion, the results of Experiment 1 clearly indicate that discrimination performance is

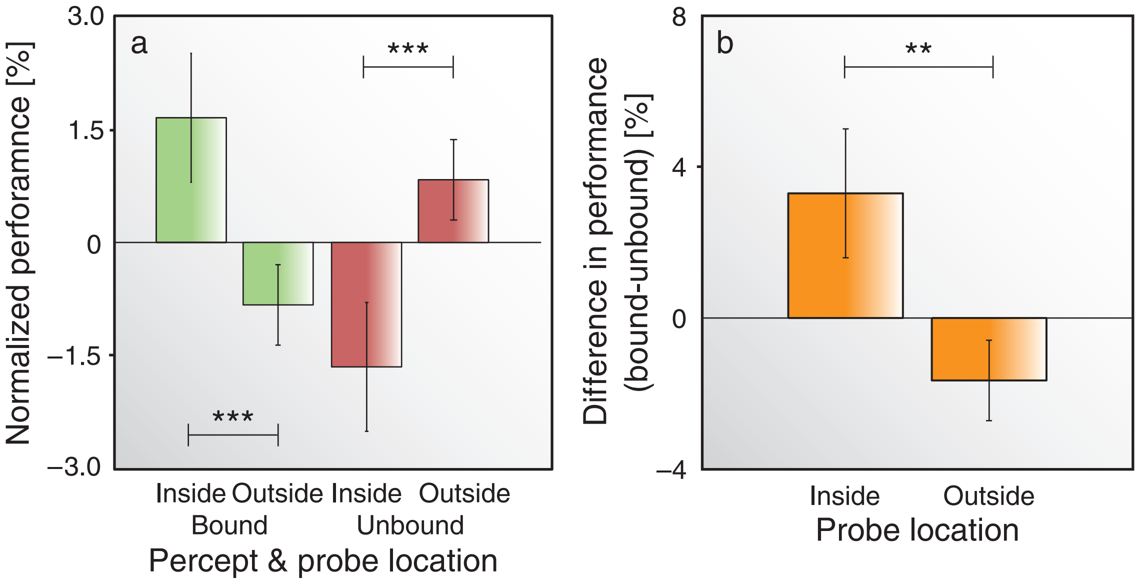

Figure 3. Performance in Experiment 2. (a) Mean and standard errors of normalized performance (mean performance was subtracted per subject) per percept and per presented probe location of either inside or outside the diamond. (b) Difference in detection performance between bound and unbound conditions separately for probes presented either inside or outside the diamond. Detection performance was higher inside the diamond as compared to outside the diamond during the bound percept. Detection performance was worse inside the diamond as compared to outside the diamond during the unbound percept.

better during the bound percept than during the unbound percept.

Experiment 2—Object area detection

In the second experiment, we tested how subjective impressions of the stimulus affected detection rather than discrimination performance. Specifically, we examined whether there were differences in detection performance between the bound and unbound percepts and whether this depended on the location of the presented probes (i.e., inside or outside the diamond). Detection performance during the bound percept was higher for probes presented inside the diamond as compared to outside the diamond (Figure 3a; $t(7) = 8.98$, $p < 0.001$). Vice versa, detection performance during the unbound percept was lower for probes presented inside the diamond as compared to outside the diamond ($t(7) = 7.50$, $p < 0.001$). Compared to the unbound percept, detection performance during the bound percept was higher and lower for probes presented inside and outside the diamond, respectively (Figure 3b; Difference: 5%; $t(7) = 3.63$, $p < 0.01$). There was no significant difference in dominance between the bound and unbound percepts ($t(7) = 2.14$, $p > 0.05$). Independent of the probe location, there was no significant difference in performance between the bound and unbound percepts ($t(7) = 1.38$, $p > 0.05$). Similarly, there were neither significant differences in reaction times between percepts (mean bound: 0.49 s, *SD*: 0.05; mean unbound: 0.49 s, *SD*: 0.05 s; $t(7) = 0.09$, $p > 0.75$) nor between locations (inside–bound versus outside–unbound: $t(7) = 0.31$, $p > 0.75$; outside–bound versus inside–unbound: $t(7) = 1.03$, $p > 0.25$). In summary, Experiment 2 showed that detection performance increased inside the object as compared to outside the object during the bound percept and that the opposite pattern was observed for the unbound percept.

Discussion

We have examined how the subjective impression of binding feature elements into an object influences discrimination and detection performance. With the ambiguous stimulus, we could distinguish between an observers' impression of a bound single-object percept and an unbound multi-object percept without change to the physical stimulus. We demonstrate that the bound percept facilitates discrimination and detection performance at and within an object's borders. Our results extend the findings by Baylis and Driver (1993) by excluding the potential confound of differences in Gestalt cues in the physical stimulus. Since our design neither included stimulus manipulations nor differences in cue constellations between the percepts, our findings show strong support for the notion that object-based benefits are a result of a higher order internal representation of an object. Thus, "objecthood" is not simply a collection of specific rules or features but a unique representational entity that confers the benefits of object-based attention.

The facilitation of processing inside the object relative to the outside in the bound condition finds its straightforward interpretation in the concept of object-based attention: Attentional resources are allocated to the object through the object's borders and inner body, and irrelevant areas around the object are suppressed. Such an interpretation is in line with physiological findings that show that neurons with receptive fields within an object have enhanced activity (Lamme, Rodriguez-Rodriguez, & Spekreijse, 1999). There are several indications that such grouping-related dynamics in activity are controlled by recurrent processes (Lamme & Roelfsema, 2000; Roelfsema, 2006).

Besides the facilitation of the region within the object and suppression outside the object in the bound condition, we observed suppression inside and facilitation outside in the unbound condition. Several explanations are conceivable for this reversal. First, it is possible that during the bound condition the object representation adapts and object-based attention is also subject to adaptation. In this view, poorer processing in the inside during the unbound percept is a consequence of this adaptation. If all the reversals were due to adaptation, both inside and outside performance should approach equality over time, for which we find no robust evidence (data not shown). Nonetheless, as adaptation likely contributes to rivalry as such (Alais, Cass, O'Shea, & Blake, 2010), an effect cannot be excluded. A second explanation would be a phenomenon related or similar to crowding (Bouma, 1970). In the unbound situation, there are more items around the inside probe that could interfere with detection (4 apertures instead of one object). The outside would be affected less, since fewer items (1 or 2) are in the immediate vicinity. A third explanation uses the spatial distribution of attention around an attended item. The localization of attention is often assumed to consist of a facilitatory central region with an inhibitory surround (Bahcall & Kowler, 1999; Carlson, Alvarez, & Cavanagh, 2007; Cutzu & Tsotsos, 2003; Hopf et al., 2006; Mounts, 2000a, 2000b; Scalf & Beck, 2010; Tsotsos et al., 1995). Similar to the bound situation, in which the outside of the object is suppressed and the inside facilitated, in the unbound condition, the *individual items (apertures)* are facilitated and *their* surround is suppressed. Quantitative predictions will depend on a large set of parameters, including width of center and surround, dynamics of attention, and the interaction between suppressive and facilitating regions. Nonetheless, it is conceivable that non-linear interaction between suppressive zones of individually attended apertures inside the diamond yields a net suppression; while outside the diamond, the suppressive zones are more separated and do interact less, and facilitation remains dominant on average. We consider it likely that all 3 explanations—adaptation, a phenomenon akin to crowding, and the spatial distribution of attention—in part contribute to the observed effect. Disentangling them in future research will foster our understanding of object-based attention.

Desimone and Duncan (1995) have argued that objects compete for limited processing capacity and that competition can be biased by top-down mechanisms that select relevant objects. In the context of the present results, it is possible that the competition between independent unbound objects decreases the processing accuracy of these objects in general. When these objects are grouped or "bound," competition disappears and processing for all bound components is facilitated. Another explanation can be extracted from the view that object-based attention is a form of an object-guided spatial attention mechanism (Davis, Driver, Pavani, & Shepherd, 2000; Martínez, Teder-Salejarvi, & Hillyard, 2007; Roelfsema, Stanisor, & Wannig, 2010; Weber, Kramer, & Miller, 1997). The grouping of independent parts or attributes as one object makes attention automatically spread evenly over the entire object (e.g., He & Nakayama, 1995; Kahneman & Henik, 1981). As many studies have presented evidence for the existence of activity patterns closely tied to such object processing in relatively high cortical areas (e.g., Cusack, 2005; Cusack, Mitchell, & Duncan, 2010; Shafritz, Gore, Marois, 2002), it is tempting to suggest that a top-down cortical mechanism is required for the perception and recognition of an object (e.g., Grill-Spector, Kourtzi, & Kanwisher, 2001) and subsequent attention allocation (O'Craven, Downing, & Kanwisher, 1999). In the light of our results, such a top-down mechanism does not rely on bottom-up feature constellations but can operate solely on the basis of high-level representations.

In conclusion, with our stimulus and design we addressed the problems inherent in the definition of an object that have challenged the interpretations of a large body of recent scientific outcomes (e.g., Baylis & Driver, 1993; Crundall et al., 2008; Gibson, 1994; Houtkamp et al., 2003). We found that the status of being an "object" is generally ambiguous and depends on the experience and interpretation of the observer. Some observers experience multiple elements in a scene as spatially separate and independent components. Others observe the same exact elements as a single object, bound by a previously stored visual representation. Objects do have to contain some specific features, such as borders, to separate them from their background, but a specific composition of features is not sufficient to produce an object. Gestalt rules such as closure and collinearity can ease and facilitate the process of binding multiple elements into a single object, but a high-level object representation is necessary to induce this process.

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