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How does our search engine "see" the world? The case of amodal completion

Jeremy M. Wolfe · Ester Reijnen · Todd S. Horowitz · Riccardo Pedersini · Yair Pinto · Johan Hulleman

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Abstract This article illustrates a dissociation between the perceived attributes of an object and the ability of those attributes to guide the deployment of attention in visual search. Orientation is an attribute that guides search. Thus, a vertical line will "pop out" amid horizontal distractors. Amodal completion can create perceptually convincing oriented stimuli when two elements appear to form a complete object partially hidden behind an occluder. Previous work (e.g., Rensink & Enns, *Vision Research, 38*, 2489–2505, 1998) has shown a preattentive role for amodal completion in search tasks. Here, we show that orientation based on perceptually compelling amodal completion may fail to guide attention. The broader conclusion is that introspection is a poor guide to the capabilities of our internal search engine.

J. M. Wolfe (✉) · E. Reijnen · T. S. Horowitz · R. Pedersini · Y. Pinto
Harvard Medical School & Brigham and Women's Hospital, Boston, MA, USA
e-mail: wolfe@search.bwh.harvard.edu

E. Reijnen
University of Friborg,
Friborg, Switzerland

R. Pedersini
University of Rochester,
Rochester, NY, USA

Y. Pinto
University of Amsterdam,
Amsterdam, Netherlands

J. Hulleman
University of Hull,
Hull, UK

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Introduction

In visual search for targets among distractors, we do not search at random. Our internal *search engine* has access to a representation of the world that can be used to guide the deployment of attention. That representation is not the same as our conscious visual experience of the world. Basic attributes such as color and orientation are processed differently for purposes of guidance. People do not typically search for a feature in isolation ("find red"). They search for something *with* that feature ("find the red apple"). Here, we consider how the image is parsed into those candidate objects of attention. In particular, we consider the role of amodal completion of objects behind occluders. In a series of experiments with a variety of stimuli, we show that image segmentation for purposes of guidance is different from image segmentation that gives rise to visual perception.

This is a tale of the dissociation between the conscious perception of form and the ability of forms to guide the deployment of attention (cf. Olivers & van der Helm, 1998). Consider Fig. 1.

On cursory examination, the two parts of the figure seem to show a black vertical and a black horizontal bar, each occluded by a white oblique bar. Suppose that we want to find the black vertical bar. We know that attention can be guided to targets on the basis of their orientation and color (Wolfe, Cave, & Franzel, 1989) or luminance polarity and orientation (Theeuwes & Kooi, 1994). Thus, in Fig. 2, it is easy enough to find the black vertical bar.

We also know—or think we know—that some occlusion information is calculated *preattentively*, without requiring

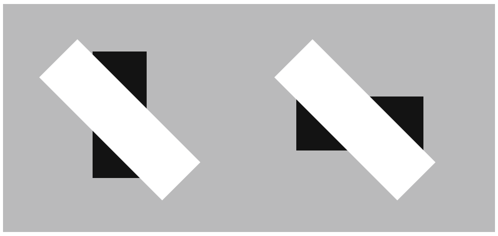


Fig. 1 A black vertical bar (on the left) and a black horizontal bar (on the right), each occluded by a white oblique bar

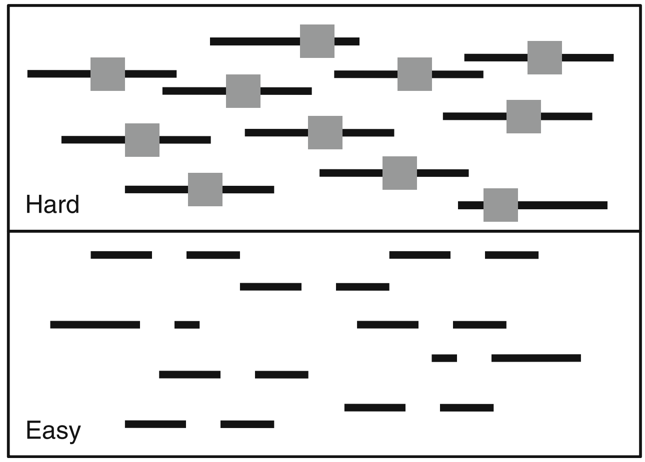


Fig. 3 After Rensink and Enns (1995). It is much easier to find the long black line segment in the *easy* search than in the *hard* search. In the hard search, the presence of a visible occluder causes the segments to complete into lines that are all of the same length

attention to each occluded item. In a series of experiments, Rensink and Enns (1998) showed that the lengths of line segments became unavailable for guiding attention if the lines appeared to continue behind an occluder, as in Fig. 3.

In the upper part of the figure, it is hard to find the long or short black segments among the medium length segments. In the lower part of the figure, with the squares removed, it seems easier, and Rensink and Enns (1998) supported this impression experimentally.

Given these facts, it seems entirely reasonable to propose that (1) occlusion occurs prior to the deployment of attention and (2) occluded objects have the properties of unoccluded objects when it comes to the guidance of attention. That is, a black vertical bar should remain a black vertical bar for purposes of guidance when occluded.

If this is the case, it should be easy to find the black vertical line in Fig. 4.

This all seemed self-evident enough for two of us to assert its truth in print (see Fig. 1 in Wolfe & Horowitz, 2004). The problem is that this assertion is not true; at least, the specific assertion about the efficiency of the search shown in Fig. 4 is not true. As will be shown below, this search is inefficient. This is not to say that occlusion is not calculated preattentively. There is evidence from multiple labs that it is (Davis & Driver, 1994, 1998; Gurnsey, Humphrey, & Kapitan, 1992; He & Nakayama, 1992; Rensink & Enns, 1995). Our purpose is to show that attentive introspection does not provide wholly accurate information about the attributes that guide attention. Orientation guides attention (Bergen & Julesz, 1983; Foster & Ward, 1991), and the black bars in Figs. 1 and 4 may appear oriented. However, those particular manifestations of orientation may not be available for guiding attention. In this article, we will attempt to shed some light on the representation of objects that can guide attention. First, we will show that stimuli of the sort shown in Figs. 1 and 4 do not produce efficient search. Next, we will show efficient search results from experiments with other "occlusion" stimuli. However, control experiments suggest that it is not completion under the occluder that accounts for the efficient search in these tasks. Instead, grouping and the outline of the grouped elements seem to be the critical factors governing the guidance of attention.

Experiment 1 Amodal completion fails to create a guiding orientation stimulus

The work of Rensink and Enns (1998), illustrated above, suggests that amodal completion can obscure a guiding

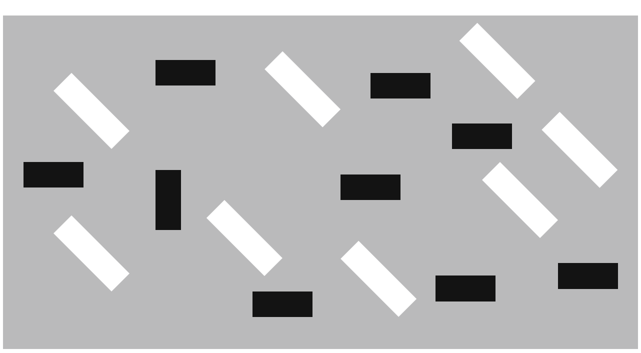


Fig. 2 Search for the vertical black bar

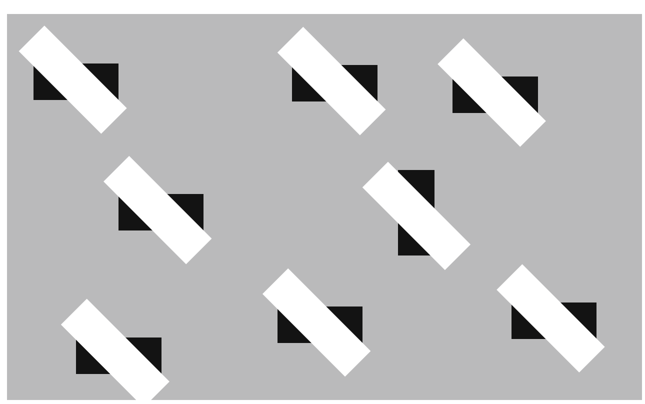


Fig. 4 Search for a vertical black bar occluded by a white bar tilted to the left

feature such as size. Indeed, we can summarize most of the previous work as suggesting that preattentive amodal completion can serve a negative role in search. Here, we tested the reverse hypothesis that amodal completion can serve a positive role by creating a guiding feature that would not exist in the absence of amodal completion. More specifically, in these experiments, we tried (and failed) to use amodal completion to create oriented bars that could support efficient visual search.

Method

Participants Sixteen students from the University of Hull (7 male; all right-handed; 18–33 years of age, with the exception of one 49-year-old) participated in return for course credit. All gave their informed consent. None of them was aware of the purpose of the experiment. All had normal or corrected-to-normal vision.

Apparatus Custom written C++ software presented stimuli and recorded responses on a PC running Windows XP. Displays were presented on a 19-in. monitor (Iiyama Vision Master Pro 454; 800 × 600, 75 Hz) controlled by a Geforce 6800 graphics card.

Stimuli Participants searched for a vertical bar among horizontal bars. Insets along the top of Fig. 5 show target–distractor pairs for the four conditions of the experiment. Bars subtended 0.5° × 1.3°. In the *basic* condition, the bars were presented in isolation. In the *front* condition, they were presented in front of diagonal rectangles (0.55° × 1.4°). In the critical *occluder* condition, they were presented behind the same diagonal rectangles, so that the bars existed perceptually only if there was amodal completion behind the occluding diagonal rectangle. Finally, in the *gap* condition, the color of the diagonal occluder was set to that of the background, so that the bar was represented by two isosceles triangles (sides 0.4°, base 0.55°) separated by a gap. This stimulus did not give rise to the impression of amodal completion across the gap. For half of the participants, the vertical and horizontal bars were black, and the diagonal rectangles were white; for the other half, this color assignment was reversed. The oblique bar, visible or not, could be tilted left or right. Thus, in the occluder and gap conditions, there were two types of targets and two types of distractors, while there was only one type of each stimulus in the basic and front conditions

The targets and distractors were presented in a virtual hexagonal grid. The grid contained three rings of hexagons, yielding a total of 36 possible locations for the items (the center of the hexagon was not available as a location). Each grid cell was 2.8° × 2.8°. The background of the stimulus displays was gray, with a low contrast random pixel array superimposed. This background was visible throughout the experiment.

Procedure For each stimulus condition, there was an initial practice block of 10 trials and another practice block of 10 trials, if necessary. When the participants felt at ease with the task, they started the experimental blocks.

A trial began with a fixation cross, presented in the center of the screen for 1,000 ms. After the fixation cross disappeared, the search display was presented for 4,000 ms or until the participant responded, whichever time was shortest. If the participants had not responded when the search display disappeared, they received another 4,000 ms to complete their response. Trials without a response were scored as incorrect. After the response, there was an intertrial interval of 1,000 ms. If the target item was present, the participants were asked to press the "present" key on the keyboard ("Z") as quickly as possible. If the target item was absent, they had to press the "absent" key

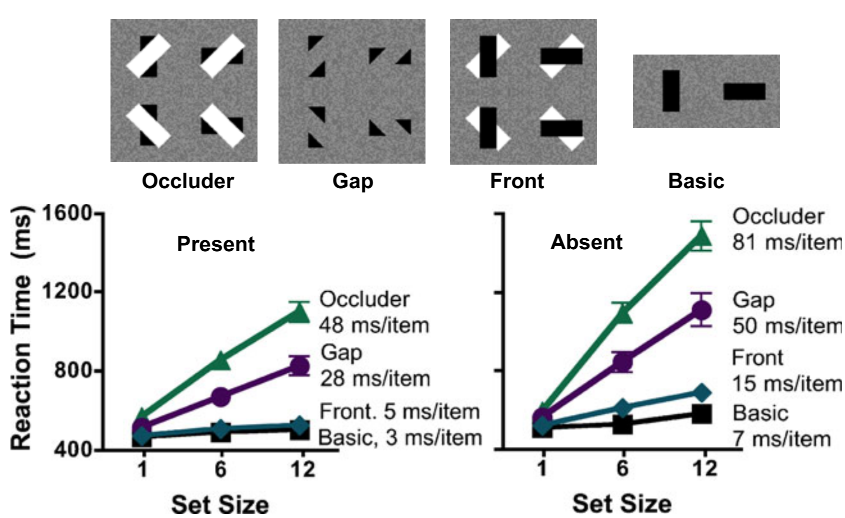


Fig. 5 Stimuli and results for Experiment 1. Error bars show ±1 *SEM* (sometimes hidden by the data point). Search for the occluded target is clearly inefficient

("N"). Present responses were given with the participants' preferred hand. After every 25 trials, there was a self-paced break, during which the participants received error feedback. Moreover, the fixation cross was used to give feedback on every trial. After a correct response, there would be a cross; after an error, there would be a minus. Error trials were not retaken. The total duration of the experiment was approximately 45 min.

There were three factors: stimulus condition (basic, front, occluder, and gap), set size (1, 6, and 12 items), and target (present vs. absent). Presentation was blocked by stimulus condition. Within each block, set size and target presence/absence were fully crossed. Each block comprised 150 trials, or 25 trials per cell. Order of stimulus condition presentation was determined by a Latin square design.

Analysis Reaction times (RTs) less than 200 and greater than 5,000 ms were rejected as outliers. All remaining trials were used in the error analysis, whereas only correct trials were used in the RT analysis. All results reported are Greenhouse–Geisser corrected, but the original degrees of freedom for the *F* values will be reported, rather than the broken degrees of freedom that the Greenhouse–Geisser correction entails. We also computed the slope of the mean RT × set size line as an index of search efficiency. For clarity of presentation, these slopes will be the primary dependent variable.

Results and discussion

Outlier removal discarded 0.2% of the data. The results, shown in Fig. 5 (collapsed over target color), do not support the hypothesis that an occluded bar behaves like an unoccluded bar. When bars are unoccluded (basic and front conditions), search slopes are very shallow, while in the gap condition, they are steep, and in the occluder condition, they are even steeper.

A 4 (stimulus condition) × 2 (target) within-subjectsANOVA on the RT × set size slopes yielded significant main effects of stimulus condition, $F(3, 45) = 118.6$, $p < .001$, $\eta^2 = .888$, and target, $F(1, 15) = 48.6$, $p < .001$, $\eta^2 = .764$, and a significant interaction between the two, $F(3, 45) = 21.1$, $p < .001$, $\eta^2 = .584$. The basic and front conditions produced RT × set size slopes for present trials near zero (3.0 and 4.6 ms/item, respectively), demonstrating that these stimuli can produce efficient pop-out search. The critical occluder condition, however, produced highly inefficient search (target present, 48.1 ms/item; target absent, 80.6 ms/item). Indeed, the slopes for the occluder condition were steeper than those for the gap condition. Paired *t* tests (corrected for multiple comparison) show that the occluder condition slopes were steeper than the slopes for each of the other conditions on both present and absent trials, all ts(15) > 7.0, all ps < .001, all η^2s > .76. The error rates tracked the pattern in the RTs. Most misses occurred in the conditions in which the search slopes were steepest.

Clearly, these results fail to support the hypothesis that the amodal orientation of an occluded bar is available to guide search. While the identity of the vertical target in the occluder condition can be readily appreciated once it is attended, it does not guide attention in the same manner as the vertical bars in the basic and front conditions. Perhaps these particular stimuli are somehow problematic. For example, the occluders could be tilted either left or right, producing two types of distractors in the occluder and gap conditions out of the single distractor type present in the basic and front conditions. Additionally, the occluders themselves might have served as distractors. This distractor heterogeneity might have disrupt the search (Duncan & Humphreys, 1989; Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992). Accordingly, we repeated the experiment with a few modifications. To anticipate the results, these also failed to produce evidence for efficient search for the orientation of amodally completed contours.

Experiment 2 Replications: A second failure to produce efficient search

We replicated Experiment 1 with two modifications designed to decrease the direct and indirect distractor heterogeneity potentially introduced by the occluders. First, we reduced the salience of the occluders by reducing their contrast relative to the occluded bars. Second, all the occluders were tilted 45° to the left, decreasing the heterogeneity of both the occluders and the occluded fragments. By reducing the salience and heterogeneity of the occluders, we gave the amodally completed bars a better chance to support efficient search.

In addition, we manipulated the distance between the two unoccluded parts of the stimuli, in order to test whether proximity could replace occlusion in making search more efficient.

Method

Participants Fourteen paid participants (9 female, 5 male) between the ages of 18 and 54 years ($M = 35.7$, $SD = 13.1$) were recruited from the local community in Cambridge, MA. All had normal or corrected-to-normal vision.

Apparatus and stimuli The experiment was run on Macintosh computers running MacOS 10.4. Experiments were programmed in MATLAB 7.5.0 using the Psychophysics Toolbox version 3.0.8 (Brainard, 1997; Pelli, 1997). Stimuli were presented on 21-in. diagonal CRT monitors, either

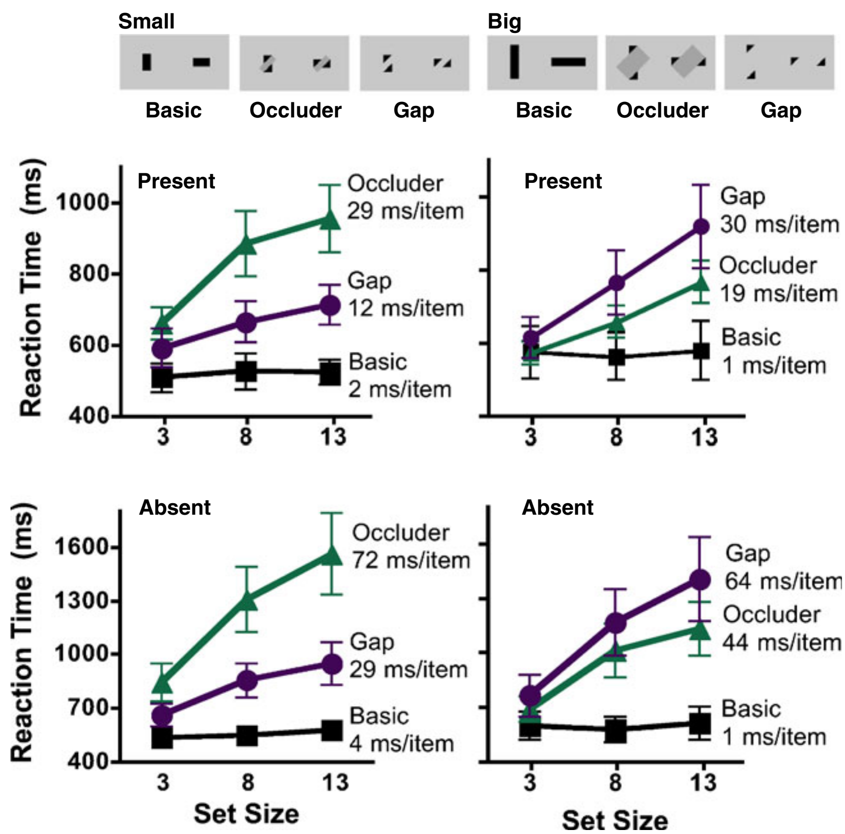


Fig. 6 Stimuli and results for Experiment 2. Error bars are ±1 *SEM*. Again, search for the occluded target is inefficient

SuperScan Mc801 RasterOps or Mitsubishi Diamond Pro 91TXM. Viewing distance was about 57 cm.

The stimuli are shown in the insets of Fig. 6. All the stimuli were presented on a light gray background. Six conditions were created by crossing three stimulus conditions (basic, occluder, gap) with two sizes (small, big). As in Experiment 1, participants always searched for a vertical target among horizontal distractors. In the small versions, the bars were 0.50° × 1.01° of visual angle, whereas in the big versions, the bars were 0.50° × 2.01° of visual angle. In the occluder conditions, the occluder was a dark gray rectangular bar tilted 45° to the right, which was placed on top of each bar. It subtended 0.35° × 1.07° (somewhat smaller than the Experiment 1 occluders) when small and 1.07° × 1.79° (somewhat bigger than the Experiment 1 occluders) when big. Stimuli were placed at random locations within a virtual 4 × 4 array with small random offsets. The search array subtended approximately 15.09° × 15.09° of visual angle. We used set sizes of 3, 8, and 13 items. The target was present in half of the displays (chosen randomly) and absent in the other half. When there was no target present, the target was replaced by a distractor.

Procedure Methods were similar to those in Experiment 1 with the following changes. Each trial started with a tone, which was followed by the search array. The search array remained visible until the participant responded. After each trial, feedback was given. For each condition there were 25 practice trials and 300 experimental trials. The order of the conditions was counterbalanced across participants. The total duration of the experiment was about 50 min.

Results and discussion

Mean RTs were calculated after excluding responses that were incorrect and those that were below 200 or above 6,000 ms. One participant was removed because 92.9% of her RTs fell outside these boundaries. From the data of the remaining 14 participants, 3.2% of the trials were removed. Mean RTs are shown in Fig. 6, along with the associated RT × set size slopes. Planned comparisons were conducted only on target-present trials.

As can be seen in Fig. 6, search was very efficient for unoccluded bars (the basic condition), while it was inefficient for both the occluder and gap conditions, replicating the results of Experiment 1. In addition, an advantage of having an occluder, rather than a gap, between parts of a single bar was seen only when the gap between parts was large.

Statistical analysis supports this summary. Slopes for both basic conditions did not differ significantly from zero, all $ts(13) < 1.452$, $ps > .170$, and were shallower than those for both the occluder and the gap conditions.

The occluder conditions all produced inefficient, significantly nonzero slopes, all $ts(13) > 5.195$, $ps < .001$. The slopes from the occluder conditions were steeper than the basic slopes for both small stimuli, $F(1, 13) = 19.846$, $p < .01$, $\eta^2 = .604$, and big stimuli, $F(1, 13) = 98.139$, $p < .001$, $\eta^2 = .883$. The gap conditions were also inefficient, yielding nonzero slopes, all $ts(13) > 4.536$, $ps < .01$, which were steeper than the basic slopes for both small, $F(1, 13) = 19.612$, $p < .01$, $\eta^2 = .601$, and big, $F(1, 13) = 25.954$, $p < .001$, $\eta^2 = .666$, stimuli.

The main difference between the two size conditions was that while the slope for the small occluder condition was steeper than that for the small gap condition, $F(1, 13) = 7.853$, $p < .05$, $\eta^2 = .377$, the opposite was true for the big stimuli, $F(1, 13) = 5.399$, $p < .05$, $\eta^2 = .293$.

Note that speed and accuracy covaried positively in this experiment. The miss error rates were low but were higher for the occluder and gap conditions (~5%) than for the basic condition (<3%).

Overall, this experiment replicated the pattern observed in Experiment 1. Search in the basic conditions was highly efficient, while it was inefficient for both the occluder and gap conditions for both stimulus sizes. Perhaps we did not do enough to reduce the salience of the occluders. In Experiment 3, we made the occluders even less similar to the search items.

Experiment 3 Extended occluders

In Experiment 3, we used an extended occluder, as shown in the inset of Fig. 7, in an effort to more clearly distinguish occluders from search items.

Method

Participants Thirteen participants (10 female, 3 male) between the ages of 21 and 54 years ($M = 34.0$, $SD = 13.2$) were tested, meeting the same requirements as in Experiment 2.

Stimuli Participants were run under the same experimental setup as that used in Experiment 2, with the following changes in the stimuli. The sizes of the bars could be small (0.63° × 1.26°) or big (0.63° × 2.51°). The 3 × 3 search array subtended 8.49° × 8.49°. Most important, while in Experiment 2 each item had its own occluder, here one occluder (a dark gray rectangle tilted 45° to the left) covered three bars at the same time. For the small versions, its size was 0.44° × 13.33°, and for the big versions, it was 1.32° × 14.24°. Basic, occluder, and gap conditions were run for both big and small conditions.

Results and discussion

Filtering out responses that were below 200 or above 5,000 ms removed 2.4% of the trials. The error rates were low (<5% for all conditions).

The pattern of results (see Fig. 7) was very similar to that in Experiment 2. This change in the occluder did not produce efficient search, as evidenced by the steep slopes in the occluder conditions. Slopes for both basic conditions were flat—that is, did not differ significantly from zero, all $ts(12) < 1.80$, $ps > .097$. These were shallower than those for either the occluder conditions [small stimuli, $F(1, 12) = 18.807$, $p < .01$, $\eta^2 = .610$; big stimuli, $F(1, 12) = 57.761$, $p < .001$, $\eta^2 = .828$] or the gap conditions [small stimuli, $F(1, 12) = 15.314$, $p < .01$, $\eta^2 = .561$; big stimuli, $F(1, 12) = 17.320$, $p < .01$, $\eta^2 = .591$].

If the orientation of the occluder interferes with search for the orientation of the occluded bars, that interference is not eliminated by making the occluder much larger than the items in the search array. This is somewhat surprising, since size serves as a guiding attribute in search (Cavanagh, Arguin, & Treisman, 1990) and one would think that it would be possible to minimize the large occluder's influence on search by guiding attention to a *short* vertical bar among short horizontal and long oblique bars. However, effective guidance of that sort does not appear to be available. If, for whatever reason, the orientation of the occluder persistently disrupts search for an oriented target, search efficiency might improve if we used unoriented occluders. We tried that manipulation in Experiment 4.

Experiment 4 Unoriented occluders

Experiment 4 brought together related stimuli from several studies. These were presented as a single unit in the interests of clarity and brevity. This does mean, however, that small differences between conditions should not be invested with much weight. The stimuli for three occluder conditions are shown in the second column of Fig. 8.

The critical change from the previous occluder conditions was that the occluder was either a square (small, 0.75° × 0.75°; big, 1.51° × 1.51°) or a diamond (1.79° × 1.79°), with no predominant axis of orientation. To retain the small black triangles as the physical manifestation of the vertical and horizontal bars (small, 0.50° × 1.76°; big, 0.50° × 2.51°), those bars became rhomboids (0.50° × 2.51°) when the occluder was a square. The number of participants is given in the final column of the figure. In other respects, this experiment followed the methods of the preceding experiments.

The target-present and target-absent slopes are given in the third and fourth columns of the figure. The two square occluder conditions produced extremely efficient search.

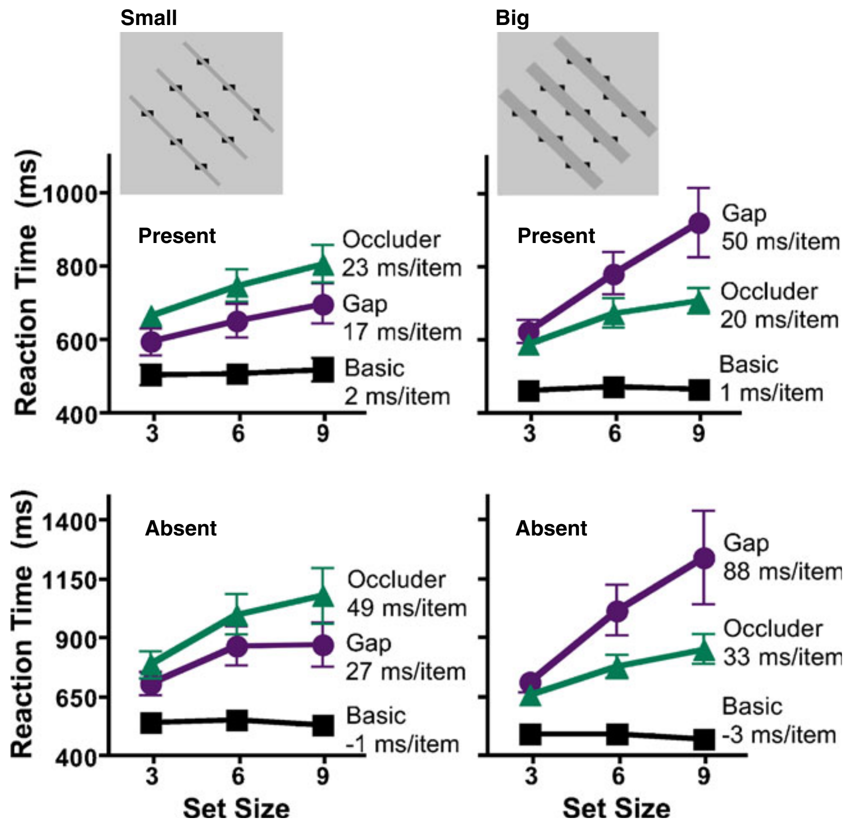


Fig. 7 Stimuli and results for Experiment 3. Error bars are ±1 *SEM*. Use of large occluders does not produce efficient search for occluded targets

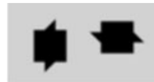
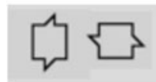
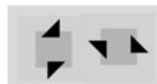
However, the diamond occluder condition produced inefficient search, even though the amodal completion of the vertical and horizontal bars looks at least as convincing as the rhomboids that amodally complete behind the square occluders. An explanation for this difference is offered by the results of the unoccluded conditions shown in Fig. 9.

If we consider the occluded rhomboid and the occluding square as forming a single item, the three unoccluded conditions maintained the outline of the item while eliminating the sense of occlusion and amodal completion. Weak amodal completion may be seen in the filled condition, but not in the outline or triangle-on square-conditions. All of these conditions also produced very efficient search. This strongly suggests that it is the orientation of the overall shape of the combined square/rhomboid that drives search performance. Apparent occlusion and amodal completion do not seem to be necessary (unoccluded conditions) or sufficient (diamond condition) to explain the results. It is clear, despite the small number of participants, that the unoccluded conditions of Experiment 4 produced much shallower slopes than did the occluded conditions in Experiments 1–3. We suspect that the critical difference is that the overall shape or "convex hull" of the items in Experiment 4 could be used to guide search,

Fig. 8 Occluder conditions in Experiment 4, with slopes for target-present and target-absent trials. Good amodal completion might (square) or might not (diamond) produce efficient search

Condition	Stimuli	Slope: Target present	Slope: Target absent	Number of observers
Small square occluder		0 ms/item	1 ms/item	12
Large square occluder		3 ms/item	3 ms/item	12
Diamond occluder		19 ms/item	39 ms/item	12

Fig. 9 Unoccluded conditions in Experiment 4, with slopes for target-present and target-absent trials. Stimuli with just the outline of the occluded figure produce efficient search in the absence of amodal completion

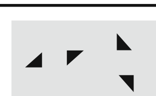
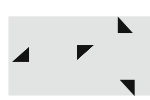
		Slope		
Condition	Stimuli	Target present	Target absent	Number of observers
Filled		2 ms/item	5 ms/item	6
Outline		5 ms/item	5 ms/item	6
Triangle on Square		4 ms/item	10 ms/item	4

whereas the convex hulls in Experiments 1–3 were not helpful. In the same vein, the diamond occluder condition shown in Fig. 8 produced inefficient search and had the least oriented convex hull. We will return to this topic in Experiment 5. The pattern of search efficiencies again illustrates the dissociation between conscious perception and guidance of attention. In all of the occlusion conditions of Experiments 1–4, the participants (and experimenters) believed that they were searching for bars that were occluded by some other object. Meantime, the participants' search engine was unable to use the orientation of those occluded bars. Instead, the search engine behaved as though it was searching through compound objects or, perhaps, objects with parts.

Figure 10 adds information from a series of gap conditions.

The efficient search in the small square gap calls into question the importance of occlusion in completing bars over a relatively short distance. The two triangles group into an oriented item without benefit of any amodal completion. Why did the larger gaps fail to produce efficient search? One explanation is that, with the larger gaps, the distance from one triangle to its mate was no less than the distance to other unrelated triangles in the field. Thus, the grouping that supported the creation of an oriented item in the small gap conditions often failed in the larger gap conditions. Alternatively, Rensink and Enns (1995) described "beta grouping" of elements that are close to each other. The large gaps might just be out of the beta range. These gap conditions add to our understanding of the unoccluded conditions shown in Fig. 9 and, potentially, to the understanding of the occluder conditions shown in Fig. 8. In the unoccluded conditions, the presence of the triangular regions gave the object an orientation. Figure 10 shows that the same triangles might not have supported orientation search by themselves. The central square region in the unoccluded conditions and, maybe, in the occluder condition served as the body of an object with parts. The body was unoriented. The parts gave the whole item an orientation. As an analogy, think of a human body with arms outstretched. The torso binds the arms to each other as part of the whole object, but we do not think of the arms as continuing through or behind the body. The mecha-

Fig. 10 Gap conditions in Experiment 4

		Slope		
Condition	Stimuli	Target present	Target absent	Number of observers
Small Square Gap		3 ms/item	6 ms/item	12
Large Square Gap		12 ms/item	42 ms/item	12
Diamond Gap		22 ms/item	58 ms/item	12

nisms of guidance may have treated the items in these experiments not as pairs of objects, one occluding the other, but as single items with parts.

Experiment 5 Collinear components and unoriented convex hulls

Experiments 1–4 presented an essentially negative result. We failed to find convincing evidence for guidance of search based on the orientation of an occluded object. Of course, the problem with such results is that there is the nagging suspicion that, if we just found the correct stimulus, we would find evidence for guidance. Experiment 5 represents our final, best attempt to find efficient search for occluded orientation. The stimuli for this experiment were designed according to two principles derived from studying the previous experiments in this series. First, Experiment 4 suggested that the results are complicated by the orientations of the convex hulls of the search items. Therefore, we designed stimuli with unoriented convex hulls, shown in Fig. 11. Second, in the previous experiments, the bar elements that gave rise to the percept of an occluded bar were triangular. It is possible that completion of the bar behind the occluder would be greater if the edges of the elements were collinear. Accordingly, square elements were used in Experiment 5. Note that it is important that the elements, themselves, should not be oriented. Collinear rectangles, like those in Fig. 3, might produce a compelling impression of completion behind the occluder. However, since the elements on either side of the occluder are oriented, a search based on orientation can be performed without the need to complete the line under the occluder. The stimuli for Experiment 5 were designed to provide no orientation cue from either the convex hull or the individual elements. However, as a glance at Fig. 11 should confirm, each stimulus produces a strong percept of either a vertical or a horizontal occluded object.

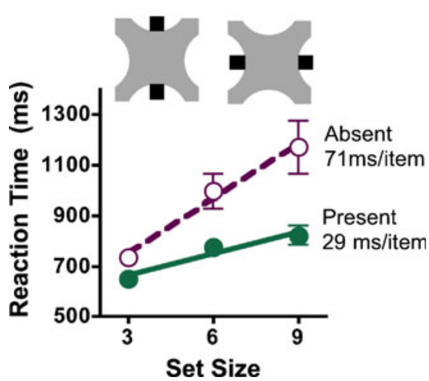


Fig. 11 Stimuli and results for Experiment 5. Error bars are ±1 *SEM*. Again, search for the occluded target is inefficient

Method

Ten participants (4 female, 6 male) between the ages of 18 and 47 years (*M* = 25.3, *SD* = 9.14) were tested, meeting the same requirements as in Experiment 2. The overall size of each element was 2.2° × 2.2°. The 3 × 3 search array subtended 17° × 17°. Each participant was tested for 300 trials, evenly distributed between three set sizes (3, 6, and 9) and target-present and target-absent trials. Methods were otherwise similar to those in the preceding experiments.

Results and discussion

Figure 11 shows the mean RTs for present and absent trials. RTs greater than 4,000 ms were excluded from analysis (just one trial). It is clear that this condition does not produce efficient search. For the target-present trials, slopes of RT × set size functions for individual participant ranged from 18 to 42 ms/item. Thus, no participant succeeded in searching efficiently for a vertical target among horizontal distractors with these stimuli. Having eliminated the confounding effect of an oriented convex hull and having given the occluded objects the advantage of collinear image elements, Experiment 5 still failed to produce evidence for guidance by the orientation of an occluded object, even though that orientation was perceptually obvious.

General discussion

It is clear that some attributes of the visual scene can be used to guide attention to items within a scene (Wolfe & Horowitz, 2004). Thus, if we are looking for an item of one color, attention is preferentially directed to objects or locations of that color (Anderson, Heinke, & Humphreys, 2010; Egeth, Virzi, & Garbart, 1984; Krummenacher, Müller, & Heller, 2001; Zhang & Luck, 2009). What has been less obvious is that the properties of an attribute such as color are different when used to guide attention than they are when they give rise to conscious perceptual experience or when they support psychophysical judgments. Continuing with the example of color, a detectable color difference may not guide attention (Nagy & Sanchez, 1990). Guidance appears to use a signal coarser than those that support perceptual just-noticeable differences (JNDs). Moreover, JNDs for guidance are not simply perceptual JNDs scaled by some constant. Perceptual JNDs form a so-called *MacAdam ellipse* around a specific color (MacAdam, 1942), but search JNDs are a quite different shape (Nagy & Sanchez, 1990). This may reflect categorical guidance by color (Yokoi & Uchikawa, 2003; Zhou et al., 2010), although this is controversial (Brown, Lindsey, & Guckes, 2010). Color differences that are perceptually identical behave very differently in the service of visual search. Thus, a desaturated red (“pink” or “peach”) target that lies at the perceptual midpoint between a saturated red and an achromatic white will be easy to find among red and white distractors, while a desaturated green that lies at the perceptual midpoint between a saturated green and an achromatic white will take much longer to find among green and white distractors (Lindsey et al., 2010). Similar dissociations between the perception of an attribute and its ability to guide attention are seen for other attributes (e.g., orientation; Hodsoll & Humphreys, 2007; Wolfe et al., 1992).

The well-known phenomenon of search asymmetry (Frith, 1974; Treisman & Souther, 1985; Wolfe, 2001) makes a similar point, although this has not been widely noted previously. In a search asymmetry, search for some *A* among *B*s is more efficient or faster than search for *B*s among *A*s. Thus, a tilted target among vertical distractors is easier to find than a vertical target among tilted distractors. This difference in the guidance of attention is not generally evident in perception. It is not at all clear that the vividness of a tilted line among vertical lines is notably greater than the vividness of a vertical line among tilted lines.

Just as the attributes that guide attention may not be the same as the attributes that we consciously perceive, the results of the present series of experiments suggest that the objects of attention are not the same as the objects that we consciously perceive. There is good evidence that attention is often, probably preferentially, directed to something akin to objects in visual search (Goldsmith, 1998; Vecera & Farah, 1994; Wolfe & Bennett, 1997). The nature of these objects of attention is less clear. We often call them *proto-objects* in order to indicate that they may not be exactly like the objects of our perception (Rensink, 2000). Stimuli like those shown in Fig. 4 may look like white bars occluding black bars, but when it comes to guiding attention, other factors seem to undermine the status of those black bars. The results of Experiments 4 and 5 indicate that the outer convex hull of the item may be one important factor in determining the orientation(s) present. Moreover, Experiment 4 suggests that the ability of the small black regions to create a guiding orientation may have less to do with amodal completion under an occluder than with proximity (e.g., the gap conditions shown in Fig. 10) and/or the grouping of pieces into a multipart object (e.g., the triangle-on-square condition shown in Fig. 9).

This is not to say that the initial stages of amodal completion (i.e., loss of border ownership) do not occur preattentively. Rensink and Enns (1998) showed that amodal completion could destroy a size cue. They also argued that amodal completion can create a size cue (see Fig. 5 of their article). However, the stimuli that produce a large target could be some sort of grouping of elements into a larger whole (as in our triangle-on-square condition), rather than requiring completion of a large line behind an occluder. In this context, it is useful to note that while Rensink and Enns (1998) found that border ownership was computed preattentively, they did not see evidence for full amodal completion ("boundary extension," in their terms) occurring preattentively.

It remains possible that the orientation of an occluded object can guide attention and that we simply failed to run the correct experiment. However, if that were so, it would seem that this guidance is a very fragile phenomenon that would be of little use in the world. For example, suppose that the simultaneous onset of the occluder and the occluded object acted to mask the occluded object in our experiments. It might be interesting to find conditions in which a stimulus onset asynchrony between occluder and occluded object produced a guiding occluded orientation signal, but it is hard to imagine when such an occasion would arise in the world outside the lab.

The failure to use occluded orientation for guidance in the experiments reported here might seem like an unfortunate limitation in our abilities, until one realizes that, like the asynchronous example just given, the stimuli used in these experiments are also unlikely to occur outside the lab. To test the hypothesis that occluded orientations guide search, we needed to create objects whose visible elements were unoriented (the little black squares and triangles). Such stimuli will be very rare in the world. If the window frame occludes a tree outside, we see the tree as continuing behind the occluder, but, at the same time, the orientation of the tree is clear from the unoccluded portions. The inability to guide to occluded orientations may never be a problem in the world.

In summary, it seems that the world is parsed into candidate objects differently by the processes that control search than by the processes to which we have direct perceptual access. We may speculate that the search engine has evolved to “see” the world in a way that is adaptive for search, even if it deviates from our perceptual experience. Just as different visual representations may serve conscious perception and motor actions (Glover & Dixon, 2002; Goodale, 1996; Haffenden, Schiff, & Goodale, 2001), there may be different visual representations serving conscious perception and internal operations such as search. Much more work will be required before we truly understand how our internal search engine sees the world.

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