Visual search for transparency and opacity: Attentional guidance by cue combination?

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A series of seven experiments explored search for opaque targets among transparent distractors or vice versa. Static stimuli produced very inefficient search. With moving items, search for an opaque target among transparent distractors was quite efficient while search for transparent targets was less efficient (Experiment 1). Transparent and opaque items differed from each other on the basis of motion cues, luminance cues, and figural cues (e.g., junction type). Motion cues were not sufficient to support efficient search (Experiments 2-5). Violations of the luminance rules of transparency disrupt search (Experiments 3 and 4). Experiment 5 shows that search becomes inefficient if X-junctions are removed. Experiments 6 and 7 show that efficient search survives if X-junctions are occluded. It appears that guidance of attention to an opaque target is guidance based on "cue combination" (M. S. Landy, L. T. Maloney, E. B. Johnston, & M. Young, 1995). Several cues must be present to produce a difference between opaque and transparent surfaces that is adequate to guide attention.

Keywords: transparency, opacity, visual search, cue combination, visual attention, surface perception

Introduction

How can we select a desired object out of the many items in our visual field? The human visual system is capable of extracting a great deal of information about the distal properties of visible objects based on the distribution of light falling on the retina. However, the last 25 years' worth of research in attention suggests that, when we search, the allocation of attention is guided by only a limited set of attributes. These include basic features such as color, orientation, size, and motion (for a recent review, see Wolfe & Horowitz, 2004). While it was once assumed that only attributes that were analyzed early in visual processing would be available to guide attention, the contemporary consensus is these attributes include properties better described as "mid-level vision." For example, attention can be guided by pictorial depth cues that are unlikely to be the product of the earliest stages of visual cortical processing (Enns & Rensink, 1990, 1993; Enns, Rensink, & Douglas, 1990; Epstein, Babler, & Bownds, 1992; Sun & Perona, 1996; Von Grünau & Dubé, 1994). Moreover, when attributes such as size, for example, guide search, it is not the retinal size of an object that is used, but the "post-constancy" size – size modulated by available depth cues (Aks & Enns, 1993).

Other attributes known to be extracted in early vision are not available to guide attention. Although line intersections, for example, are available early on in the visual system (e.g., He & Nakayama, 1992), they do not produce efficient search (Wolfe & DiMase, 2003). Rensink and Enns (1995) demonstrated that not only is low-level information not guiding the deployment of attention, early information about properties like the length of line segments is actually preempted by higher order representations. Processes such as those generating the Müller-Lyer illusion can hide information that would otherwise be available to guide visual search. This class of findings led Nakayama and He (1995) to propose that attention is directed to surfaces, rather than objects, and to suggest that attention would be guided only by surface properties.

Real world surfaces can be categorized as transparent or opaque. If surface features are the guiding attributes, can attention be guided toward transparent and/or opaque objects? Note that transparency and opacity are unusual

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features because they are defined only in the presence of another surface. An item on a computer screen can be red or big or vertical without reference to another visible item (e.g., "big" could be relative to a remembered standard). That same item cannot be transparent or opaque in splendid isolation.

The goal of this work is to determine whether transparency and/or opacity serve as guiding attributes in visual search. Mitsudo (2003) performed a series of experiments that show transparency information can be used to create objects that are sought efficiently (his Experiments 1 and 2) and to disable image attributes that support efficient search (his Experiment 3). These results show that transparency information, like intersection information, is available early in visual processing. Mitsudo shows that we can search for rectangles that would not exist if early vision were insensitive to the rules of transparency. We wish to know if observers can guide attention by transparency itself.

This distinction can be made clearer by considering guidance by color and orientation. It is possible to guide attention to a vertical bar that would not exist if the early visual system were insensitive to color information. Imagine red vertical and horizontal bars on an equiluminant green background (Cavanagh, Arguin, & Treisman, 1990). At the same time, it is possible to guide attention on the basis of the redness itself. Imagine a search for the red bar among green bars on a gray background. It is the latter sort of evidence we seek in this study. Can attention be guided to transparent among opaque objects or vice versa?

To answer this question, we performed a series of visual search experiments. Guidance can be inferred from the pattern of results from experiments where observers search for a target item among varying numbers of distractor items. Reaction time (RT) is plotted against set size (the total number of display items, target + distractors). This RT × set size function indexes the cost of adding another distractor to the display, and is taken as a measure of search efficiency. Shallower slopes represent more efficient searches. If the RT × set size function is flat (slope of 0), the target can be detected independently of the number of distractor items, and is often said to "pop out" of the display. A flat (or nearly flat) slope is a classic diagnostic for a guiding attribute in search (Treisman & Gelade, 1980). Steep slopes, on the other hand, suggest that attention is necessary to discriminate targets from distractors. Finding a rotated T among rotated L distractors is one example of such an inefficient search, where the addition of each new distractor item adds around 20–30 ms to the search time (Kwak, Dagenbach, & Egeth, 1991).

A stimulus feature is not a guiding attribute independent of context. For example, a red item will be found efficiently among green distractors but not among reddish orange distractors. The difference between target and distractor is critical (Duncan & Humphreys, 1989). A more curious aspect of the relationship of targets and distractors is that this relationship can be asymmetric. In some cases, the roles of target and distractor can be reversed without much consequence. It is easy to find red among green or green among red. In other cases, this is not true. For example, it is easier to find a moving target among stationary items than a stationary target among moving items (Dick, 1989; Royden, Wolfe, & Klempen, 2001). Treisman and Gormican (1988) first suggested that search asymmetries could be a useful tool by noting that the presence of a feature can guide attention better than its absence. Thus, we could argue that motion is a feature and stationarity only its absence (but see Rosenholtz, 2001). Applying this search asymmetry logic, one would test search for A among B, and B among A. If one search produces shallow slopes and the other steeper slopes, then one could argue that the target producing shallow slopes bears the feature, and the other target is defined by the absence of the feature. Note that there are asymmetries where *both* searches produce steep slopes but where one is markedly steeper than the other (e.g., search for upright among inverted faces, Tong & Nakayama, 1999). In such cases, neither property can be said to guide search. The difference in slopes is most likely a reflection of different rates of serial processing of items. Additionally, in some more complex cases, like detection of shadows, it is possible for the absence of a specific feature to alter the structure of a scene. In that case, it might be absence that is detected more readily than presence (Rensink & Cavanagh, in press).

In this work, we demonstrate that attention can be guided to the presence of an opaque object with considerable efficiency. Transparency, the absence of opacity, is harder to find. In initial work, we found that searches for static opaque surfaces among transparent surfaces, and vice versa, were extremely inefficient. In Experiment 1, search for a moving opaque item among moving transparent items was quite efficient while the reverse was less efficient. Experiment 2 shows that the motion cues, while apparently necessary, are not sufficient to support efficient search. Experiments 3 and 4 show that violations of the physics of transparency disrupt search, while showing again that the motion differences between stimuli are not sufficient for efficient search. Experiment 5 shows that search becomes inefficient if X-junctions are removed. Experiments 6 and 7 show that efficient search survives if X-junctions are occluded. It appears that guidance of attention to an opaque target is guidance on the basis of "cue combination" (Landy et al., 1995). Several cues must be present to produce a difference between opaque and transparent surfaces that is adequate to guide attention.

Initial studies: Static stimuli

As can be seen in many works of art and in many articles in the scientific literature, transparency and opacity can be effectively portrayed with static stimuli. We examined the ability to use this information to guide attention in a series of initial investigations with a variety of stimuli. Figure 1 shows an example using circular stimuli on a contoured background. In this case, an appearance of transparency was created by placing a virtual blue disk on an achromatic background. The disk behaved like a filter that would pass a percentage of blue light while reflecting blue from its surface. Opaque distractors were created by shifting the disk so that the contours within the disk did not align with the contours of the background. The resulting T-junctions indicated occlusion, and therefore opacity, just as the X-junctions indicated transparency. Thus, the disk at the center appears more transparent than the other four disks in Figure 1.

We report these experiments only briefly because pilot work with a variety of static stimuli consistently produced extremely inefficient search. Using stimuli like those in Figure 1, search for an opaque disk among transparent distractors produced average RT x set size slopes of 142 ms/item on target present trials and 356 ms/item for target absent. Search for a transparent disk among opaque distractors was even worse, with target present slopes of 210 ms/item and target absent slopes of 339 ms/item. In this example, set sizes were 1, 2, and 3 items and there were seven observers. Control experiments demonstrated that this was not a failure to detect transparency away from fixation. Observers could reliably (83% correct) discriminate a single transparent from opaque stimulus in the periphery in a 150-ms flash–too brief to perform a voluntary saccadic eye movement. Nevertheless, these very steep search slopes indicate that observers may have felt a need to fixate each item in turn.

In spite of the range of beautiful transparency illustrations in the literature, we never found a static display that produced search slopes that fell even in the range of typical inefficient (T vs. L) search. That in itself is of some interest as a negative finding. The transparency and opacity of these items were introspectively clear, yet search proved to be extremely inefficient. Accordingly, in the experiments described more fully below, we used stimuli in which simulated opaque and transparent surfaces moved over a textured background.

It is interesting that Mitsudo's (2003) experiments worked with static stimuli. In his tasks, the rules of transparency were creating distinctive objects. In our research, we wished to distinguish between objects that were identical except for their transparency or opacity. In distinguishing between transparent and opaque objects like those in Figure 1, the visual system must decide how to assign contours that lie within the object's boundaries. This is the problem of "scission" (e.g., Singh & Anderson, 2002). Apparent transparency is made more compelling if scission is made more compelling, and scission of surfaces is made easier if they are moving independently (D'Zmura, Rinner, & Gegenfurtner, 2000). As we will see, while relative motion alone is not adequate to guide attention efficiently, when it is combined with other cues to transparency/opacity, search for an opaque item proceeds with relative ease.

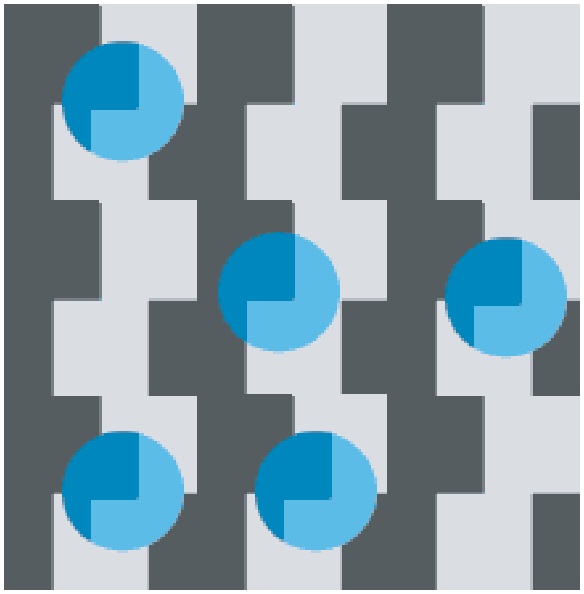

Figure 1. Static transparent and opaque stimuli used in pilot investigations.

Experiment 1: Search for moving transparent and opaque targets

In Experiment 1, we had observers search for transparent targets among opaque distractors or vice versa. Experiment 1a used small set sizes (1-4), while Experiment 1b tested the same effect at larger set sizes.

Experiment 1a: Method

Observers

Twelve observers from the paid observer panel of the Visual Attention Laboratory at Brigham and Women's Hospital in Boston participated in this experiment. All passed the Ishihara test for color blindness and had 20/25 corrected vision or better. Observers gave informed consent and were compensated $10/hour for their time.

Apparatus and stimuli

In this and all subsequent experiments, stimuli were presented on a 21" Mitsubishi monitor running at a refresh rate of 75 Hz and with a resolution of 1024 x 768 pixels controlled by a Power Macintosh G4 running Mac OS 9.2.2. Stimulus presentation and data collection were controlled by a Matlab 5.2 (MathWorks) script using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Stimuli were viewed in a dark room at a viewing distance of 57.4 cm.

The stimuli consisted of simulated opaque and transparent bars (15° x 1.5°) moving over a grayscale texture of dots (Figure 2). Backgrounds subtended 23° x 23° and consisted of 500 dots (diameter = 2.0°) positioned randomly atop a light gray (29.0 cd/m^2) backdrop. Each dot assumed one of four luminance values (Dot A = 25.1 cd/m^2, Dot B = 14.2 cd/m^2, Dot C = 6.6 cd/m^2, and Dot D = 1.3 cd/m^2), and dots could occlude one another. The region surrounding each background was solid black (0.7 cd/m^2).

A filtered version of the background was created by transforming RGB values according to Equation 1:

$$\begin{bmatrix} ro \\ go \\ bo \end{bmatrix} = \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.8 & 0 \\ 0 & 0 & 0.6 \end{bmatrix} \begin{bmatrix} ri \\ gi \\ bi \end{bmatrix} + \begin{bmatrix} 10 \\ 10 \\ 10 \end{bmatrix}. \qquad (1)$$

The multiplicative component acts as a greenish filter. The additive component simulated a diffuse, achromatic reflectance from the filter's surface (and made the stimuli look more compelling). This resulted in transparent colors with CIE coordinates of x = 0.272 and y = 0.385 and a range of luminance values (backdrop = 16.2 cd/m^2, Dot A = 14.4 cd/m^2, Dot B = 8.5 cd/m^2, Dot C = 4.1 cd/m^2, and Dot D = 0.1 cd/m^2). Transparent stimuli were created by pasting the filtered version onto the corresponding region of the unfiltered background. Opaque stimuli were obtained by randomly cutting a portion of the filtered version and moving it across the background (with the constraint that the sampled stimuli never overlapped the original background). As shown in Figure 2, texture within the opaque bar remained unchanged as the bar moved over the background, whereas the texture within the transparent bar changed, consistent with a transparent bar moving over a visible texture.

Opaque and transparent bars were horizontally centered on the background (4.0° from either edge) and motion was confined to the vertical dimension. (In exploratory work, we added a modest horizontal component to the motion without changing the results.) The stimuli were randomly assigned to 15° x 3° cells within a moving 1 x 4 grid (see Figure 2). The overall vertical motion of all bars was driven by a sinusoidal oscillation with an amplitude of 4.9° and a period of 2720 ms. Additionally, each opaque and transparent bar was given an independent vertical motion with an amplitude 0.5° and a period one fifth of the period of the overall motion (544 ms). The phase of this component was different for each bar. Thus, the added component served to disrupt the sense that the moving items formed a single object. The grid of four possible stimulus locations began each trial at the center of the display. Starting direction of motion was chosen at random. In the course of their motion, bars' edges could come as close to each other as 0.5° or go as far away as 2.5°. They could come as close as 0.8° to the edge of the background.

Search displays included a central fixation point with a red center (0.8° x 0.8°, 9.1 cd/m^2, CIE coordinates: x = 0.629, y = 0.342) and yellow surround (0.2° thick, 43.8 cd/m^2, CIE coordinates: x = 0.400, y = 0.515). The fixation point occluded the opaque and transparent stimuli as they passed through the center of the display.

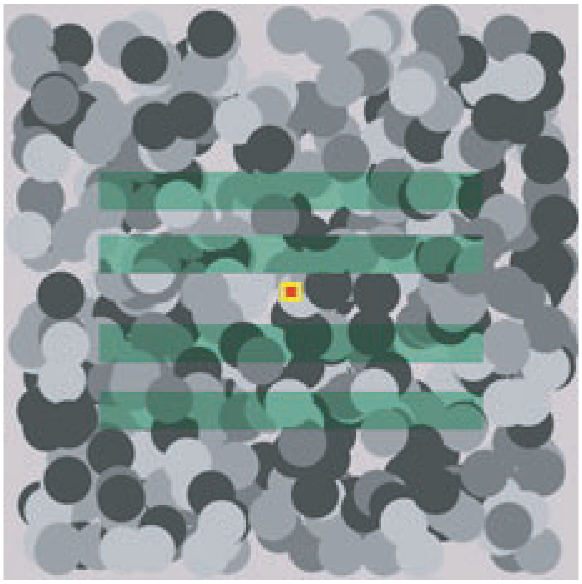

Figure 2. Movie of typical stimuli used in Experiment 1a: a search for an opaque target among transparent distractors.

Procedure

Observers searched for an opaque bar among transparent bars and vice versa. Blocks of opaque and transparent search trials consisted of 40 practice trials and 300 test trials. The order of these conditions was counterbalanced across observers. A new background was generated for each condition. Before the start of a condition, observers were told what the target and distractors would be. There were four set sizes: 1, 2, 3, and 4 items. A target was present on 50% of trials. Set size, presence or absence of the target item, and position of search stimuli were randomly chosen across trials. A tone accompanied the appearance of the background at the beginning of each trial, after which search stimuli appeared 500 ms later. Stimuli remained visible until the observer pressed one of two keys, a "yes" key if the target was detected or a "no" key if not. Feedback was provided after each response in the form of text that remained on screen for 400 ms and a beep if an error was made. Observers were instructed to respond as quickly and accurately as possible.

Data analysis

RTs faster than 200 ms and greater than 4000 ms were discarded. All data from an observer were discarded if error rates in at least one cell exceeded 25%. Such error thresholds are somewhat arbitrary. We wished to remove observers who were very incautious outliers in our population. Removal of these observers "cleans up" the data but does not alter the pattern of results. As noted below, error rates in these experiments are somewhat higher than typical in visual search. In general, the higher error rates occurred in condtions that produced less efficient search–a speed-accuracy covariance.

Results

Data from one observer were excluded due to the error criterion. Discarding fast and slow RTs did not result in excluding more than 1% of any observer's data. Figure 3 shows the mean correct RTs as a function of display size for both target present and target absent trials.

A one-sample *t* test on the target-present slopes showed search rates to be significantly different from 0 ms/item for both opaque targets among transparent distractors, $t(10) = 3.4$, $p < .01$, and transparent targets among opaque distractors, $t(10) = 6.9$, $p < .01$. Slopes for the opaque target were significantly shallower than those for the transparent target, $t(10) = 2.4$, $p < .05$.

The target-absent data were somewhat unusual. Typically, target absent RTs are slower than target present, and RT x set size slopes for target absent trials are steeper than corresponding target present slopes (Wolfe, 1998). Figure 3 shows that neither of these results holds in the present case. Target absent slopes are shallower than the corresponding target present slopes, $t(10) = 2.5$, $p < .05$ for opaque targets and $t(10) = 4.5$, $p < .01$ for transparent targets, and, at least for the larger set sizes, mean RTs are comparable for present and absent trials. Recently, we have found unusual patterns of results with small set sizes (Michod, Wolfe, & Horowitz, 2004). Accordingly, we will present a replication of the basic experiment with larger set sizes (see Experiment 1b) before considering the implications of this pattern of results.

As shown in Figure 4, error rates are somewhat higher than is typical for visual search experiments. As a somewhat arbitrary comparison, our recent study of the featural status of intersections (Wolfe & DiMase, 2003) produced miss error rates between 1.3% and 6.5%, depending on condition and averaged across set size. False alarm rates in those experiments averaged less than 1%. False alarms are typically very rare in search tasks with RT as the dependent measure. The higher error rates here suggest that the opaque and transparent bars are more confusable than many other search stimuli. The miss errors increase with set size. This means that the "true" hit trial RTs, in particular, are probably slower than measured RTs. Townsend and Ashby (1983) suggest dividing RT by accuracy as a way to estimate the true RT. If we do that for the data in Experiment 1a, the resulting slopes are 20 ms/item for opaque targets and 33 ms/item for transparent targets. Thus, while there is evidence for an asymmetry favoring opaque targets, the evidence that opacity is a guiding attribute is not particularly strong in this experiment.

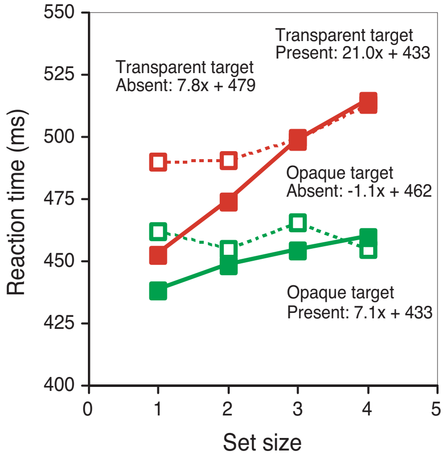

Figure 3. RT x set size functions for search for opaque among transparent stimuli and vice versa (opaque target = green symbols, transparent target = red symbols). Solid lines and symbols are target present data; dashed lines and hollow symbols are target absent. Slopes are given with the data.

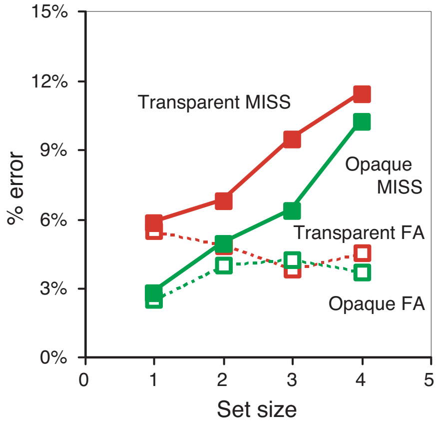

Figure 4. Miss and false alarm (FA) error rates as a function of set size for the opaque and transparent target conditions of Experiment 1a. Solid lines and symbols are misses and dashed lines with hollow symbols are false alarms. Opaque stimuli are shown with green symbols, and transparent stimuli are shown with red symbols.

Experiment 1b: Larger set sizes

Because some of our recent work (Michod et al., 2004) suggests that search with small set sizes may produce different patterns of results than search through larger sets of items, Experiment 1b repeats the basic experiment for set sizes between 4 and 16.

Methods

Observers

Twelve observers from the Visual Attention Laboratory's paid observer panel participated in this experiment.

Stimuli

Compared to Experiment 1a, the opaque and transparent bar stimuli were reduced in width (from the original 15° to 2.9°) allowing for a 4 x 4 grid of possible stimulus locations. There was 1.0° between adjacent columns of stimuli. Motion of the stimuli followed the same rules as before but was slightly slowed. A complete cycle took 3200 ms.

Procedure

There were four set sizes: 4, 8, 12, and 16 items. In all other respects, the procedure was similar to that for Experiment 1a.

Results

Data from two observers were excluded due to the error criterion. Discarding fast and slow RTs did not result in excluding more than 1% of any observer's data. Figure 5 shows the mean correct RTs as a function of display size for both target present and target absent trials.

The target present results for larger set sizes duplicate the basic pattern seen with the smaller set sizes. Search for an opaque target is faster and more efficient than search for a transparent target, $t(9) = 3.1$, $p < .05$. Target absent trials show a fairly typical pattern for the transparent case. Slopes are marginally steeper than those for target present, $t(9) = 2.2$, $p = .057$. The pattern for target absent trials in the opaque target condition remains atypical. The slope is close to zero, $t(9) = 0.18$, $p = ns$ (though, note that the mean RTs are substantially slower than those shown in Figure 3 for a comparable condition of Experiment 1a).

Error rates are again somewhat higher than typical in search experiments. Misses averaged 6.8% for opaque targets and 6.9% for transparent targets, with false alarm rates of 2.6% and 2.4%, respectively. Correcting hit RTs for accuracy, as described above, changes the slopes to 7.2 ms/item for the opaque targets and 21.8 ms/item for transparent targets.

Discussion

Several aspects of the results of Experiment 1 are noteworthy. First, unlike with static stimuli, all of the search efficiencies are in range of typical laboratory search tasks that do not require fixation of each potential target in turn. Moving the stimuli over a textured background made the distinction between opacity and transparency sufficiently salient to study with these methods. Second, the results are asymmetric. Search for an opaque target is more efficient than search for a transparent target. In the typical understanding of search asymmetries, this would suggest that opacity is the "feature" and "transparency" is the absence of opacity. The claim of featural status for opacity is complicated by the relatively high error rates in these experiments. Correcting for errors preserves the asymmetry, so it is not the case that the difference between opacity and transparency searches is produced by a speed-accuracy tradeoff. While the error correction made the slopes in Experiment 1a steep enough to weaken claims for an efficient opaque feature search, the corrected slopes for opaque targets in Experiment 1b were still quite efficient. Moreover, the error correction makes a much less dramatic change in the slopes in Experiment 1a if two observers with rather high error rates are removed from the analysis.

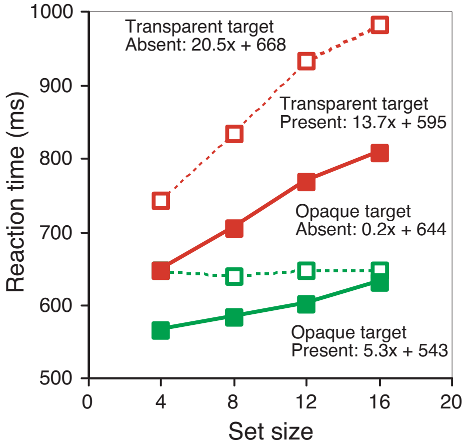

Figure 5. RT x set size functions for search for opaque among transparent stimuli (green symbols) and vice versa (red symbols) using larger set sizes. Solid lines and symbols are target present data; dashed lines and hollow symbols are target absent. Slopes are given with the data.

In the course of several experiments designed to uncover the guiding cues to opacity and transparency, we have run a number of replications of the basic experiment described here. These are summarized in Table 1 (RT x set size slopes) and Table 2 (error rates). Here, and elsewhere, correction for errors changes the specific values for slopes but it does not change the overall pattern of results. Accordingly, we will report the uncorrected slopes and give an account of errors.

In all 10 versions of the experiment, search for opaque targets among transparent distractors was more efficient than the reverse. Moreover, target absent slopes in the opaque target condition were always highly efficient. On these trials, when all items are transparent, it appears to be very easy to determine that nothing is present. Taken as a group, the results suggest that observers can guide their attention to opaque items in the display with reasonable efficiency. Even corrected for errors, the average target present slope for finding opaque targets is 12.6 ms/item (Experiment 1a is actually the worst case). The average corrected slope is 30.6 ms/item for search for a transparent target. Something is guiding attention toward the opaque targets and is very efficiently allowing observers to determine when no opaque target is present.

The results of the basic experiment do not establish exactly what aspect of the stimulus is critical. As seen in Figure 2, moving transparent and opaque stimuli differ in a number of ways that involve other guiding attributes. Consider a single opaque or transparent stimulus as it moves across the background. Contours internal to the stimulus move if the stimulus is opaque. They are "stuck" to the opaque surface. Is search for an opaque stimulus merely an

Set size range	Background dot size	Opaque present	Transparent present	Opaque absent	Transparent absent
1 to 4	Large	6.8	16.9	1.2	15.2
1 to 4	Large	13.5	16.5	-2.9	7.9
1 to 4	Large	6.0	14.3	-0.3	10.0
1 to 4	Large	9.4	16.0	-3.9	5.8
1 to 4	Large	7.1	21.0	-1.1	7.8
1 to 4	Large	5.1	20.3	3.9	15
1 to 4	Small	7.4	15.7	0.3	2.9
4 to 16	Large	5.3	13.7	0.2	20.5
4 to 16	Small	1.6	9.4	0.1	12.4
1 to 4	Scene	10.1	41.2	5.8	29.3
Average:		7.2	18.5	0.3	12.7

Table 1. Multiple replications of the basic search for opaque among transparent items and vice versa. Slopes are standard RT x set size functions and are not error corrected. Note that search for opaque among transparent is typically quite efficient and is always more efficient than search for transparent among opaque.

Set size range	Background dot size	Opaque present	Transparent present	Opaque absent	Transparent absent
1 to 4	Large	4.2%	5.6%	3.0%	3.8%
1 to 4	Large	6.3%	6.3%	2.8%	3.1%
1 to 4	Large	5.9%	6.3%	2.2%	3.1%
1 to 4	Large	7.7%	8.1%	4.3%	5.9%
1 to 4	Large	6.1%	8.4%	3.6%	4.7%
1 to 4	Large	4.8%	5.5%	3.2%	3.0%
1 to 4	Small	7.8%	6.7%	4.1%	3.5%
4 to 16	Large	6.8%	6.9%	2.6%	2.4%
4 to 16	Small	3.1%	7.1%	2.5%	1.5%
1 to 4	Scene	4.7%	3.7%	1.3%	3.7%
Average:		5.7%	6.5%	3.0%	3.5%

Table 2. Corresponding error rates for the multiple replications of the basic search for opaque among transparent items and vice versa. In general, these error rates are somewhat higher than those measured in typical feature search tasks. However, error-corrected slopes remain shallow for opaque targets. Error rates are higher for transparent targets. Thus, correcting for errors enhances the asymmetry between opaque and transparent.

example of search for this motion cue? This hypothesis is tested in Experiment 2. Transparent filters change stimuli in ways limited by the physics of the situation. For example, regions do not increase in luminance as they move behind filters. Experiments 3 and 4 assess sensitivity to violations of these physical rules. Moving opaque bars create accretion and deletion cues at their borders as T-junctions are formed with abutting background contours. Transparent stimuli create specific types of X-junctions as background contours traverse their borders. The role of these spatial constraints is evaluated in Experiments 5-7.

To anticipate our conclusions, the data suggest that opaque surfaces are more *object-like* than transparent surfaces. Search for the presence of an opaque item is search for the presence of an object. Search for the presence of a transparent item is search for the relative absence of an object, and is thus more difficult. Violating any of the cues to transparency makes the transparent item more object-like, and thus harder to distinguish from an opaque item.

Experiment 2: Is efficient search due to motion cues within the bar?

In principle, the search for the opaque item among transparent (or vice versa) in Experiment 1 could have been a motion search. A dot on the opaque item moves relative to the rest of the background while a dot under the transparent filter does not. In the frame of reference of individual items, the dots internal to the transparent items move as the item moves, while the dots internal to the opaque items are fixed. If observers performed the task in Experiment 1 solely on the basis of the motion of dots within the search items, then the same pattern of results should be obtained if we move the same bars (with the same contents) over a blank, dark background. The search items would not be transparent and opaque, though the transparent stimuli could be seen as windows in a black surface, looking through to a textured background. Importantly, the contours inside the once-transparent bars would still move while the contours in the formerly opaque bars would remain fixed to the moving bar.

Method

Observers

Fourteen observers from the Visual Attention Laboratory's paid observer panel participated in this experiment.

Stimuli

The stimuli were identical to Experiment 1a, with the addition of two new conditions in which the background was not shown (Figure 6). In these conditions, bars appeared against a uniform black (0.7 cd/m^2) background. The opaque bar contained an unchanging texture that moved with the bar and the transparent bar had a scrolling motion of dots that appeared and disappeared. Transparent bars were consistent with a moving window in a black surface, opening onto a textured background. Concealing the background eliminates the cue of junction type because the black background forms only T-junctions with the textures in both transparent and opaque bars.

Procedure

Observers were tested in four blocked conditions: search for an opaque bar among transparent bars and vice versa with visible backgrounds, search for a transparent bar among opaque bars and vice versa with hidden backgrounds. The first two conditions were a replication of Experiment 1a and are reported in Tables 1 and 2. Blocks consisted of 40 practice trials and 300 test trials. The order of conditions was counterbalanced across observers. There were four set sizes: 1, 2, 3, and 4 items.

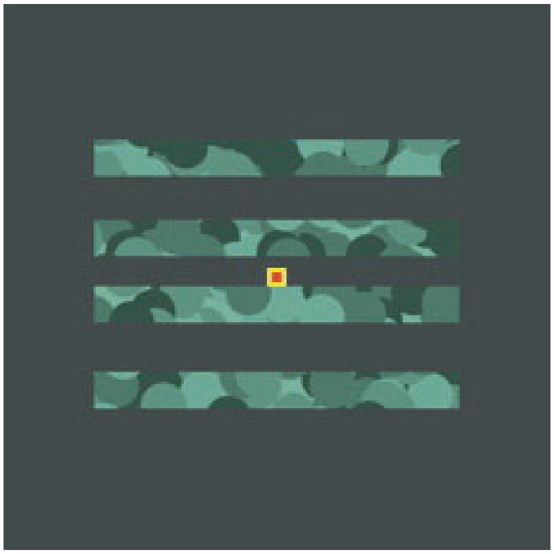

Figure 6. Movie of typical stimuli used in the no background conditions of Experiment 2.

Results and discussion

Discarded fast and slow RTs constituted no more than 1% of any individual's data. Data for one observer were excluded for violating the error criterion. Figure 7 shows the mean correct RTs as a function of set size for both target present and target absent trials. Error data are shown in Table 3.

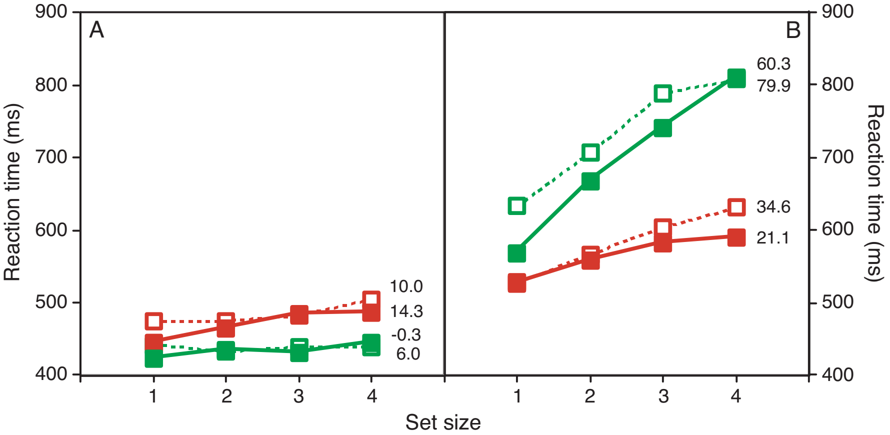

Figure 7. RT x set size functions for search for opaque among transparent stimuli (green symbols) and vice versa (red symbols). Solid lines and symbols are target present data; dashed lines and hollow symbols are target absent. Slopes are given to the right of the data. The with background cases (Panel A) are a replication of Experiment 1a, showing an advantage for the opaque targets. From top to bottom, slopes are given in this order: transparent absent, transparent present, opaque absent, and opaque present. In the no background conditions (Panel B), only the moving bars are presented. The asymmetry reverses and search becomes markedly slower and less efficient.

Background	Yes		No		Yes		No	
Target type	Opaque	Transparent	Opaque	Transparent	Opaque	Transparent	Opaque	Transparent
Set size	MISS % (target present)				FA % (target absent)			
1	5.1%	2.7%	5.3%	10.7%	2.2%	3.9%	7.5%	2.6%
2	6.3%	5.3%	9.0%	7.8%	3.5%	2.1%	7.6%	4.6%
3	4.2%	7.8%	14.9%	6.4%	2.2%	2.0%	7.6%	4.6%
4	8.1%	9.5%	20.1%	12.9%	1.3%	4.5%	9.7%	10.5%

Table 3. Error rates for Experiment 2. Error rates are high for simple search tasks but note that they are *higher* when the background is removed, showing that better RT performance with a background is not the result of a speed-accuracy tradeoff. FA = false alarm.

It is clear that the motion cue within the bars in Experiment 2 is not sufficient to produce performance like that in Experiment 1. Removing the background made search notably worse. This was especially true for the opaque target condition, where slopes went from about 6 ms/item to about 80 ms/item.[1] Efficiency of the search for a transparent target was less affected, though mean RT was somewhat slowed. The removal of the background introduces an occlusion cue into the nominally transparent stimuli. Dots in those bars appear and disappear–something that does not happen in the opaque bars. This may have been the signal that observers used to perform the task and it might have actually interfered in some fashion with the motion cue.

Error rates increased when the background was removed, showing that the difference between conditions was not due to a speed-accuracy tradeoff.

Another indication that the motion cue is not sufficient to explain the results of Experiment 1 is that the search asymmetry is reversed in Experiment 2. The scrolling dots of the transparent bars are easier to search for than the static dots of the opaque bar. Our initial work indicated that motion of the items was necessary to permit efficient search for an opaque target among transparent distractors. Experiment 2 showed that the motion of the items in the absence of the background is not sufficient.

Experiment 3: Preserving motion while violating transparency–impossible filters

Perhaps the sufficient cues in the basic opaque versus transparent search are relative motion cues between items and the background. A dot on an opaque surface moves relative to a dot on the background. A dot, visible through a transparent surface, does not move relative to a dot on the background. Relative motion cues are more salient than absolute motion: Think of the motion of a cloud in the open sky compared to the motion of the same cloud passing in front of the moon (Aubert, 1886, reported in Graham, 1965). Relative motion would have been eliminated by the removal of the background in Experiment 2. If relative motion cues between background and search items are sufficient, then performance should not be impaired if we violate the rules of transparency while preserving the motion. In previous experiments, the bars consisted of an image of the background as seen through a greenish filter. All of the contours of the background were preserved in the filtered image, and color and luminance were consistent with the physical effects of a green filter. In the present experiment, we created an image that did not correspond to the effects of any physical filter. All contours were preserved, but a "false color" filter was introduced, which had the effect of replacing each underlying gray dot with a dot of randomly generated RGB values (Figure 8). These are very colorful, but not physically plausible. The false color opaque items were simply patches of the false color image that were randomly selected from the background in the same manner as the opaque bars of Experiment 1.

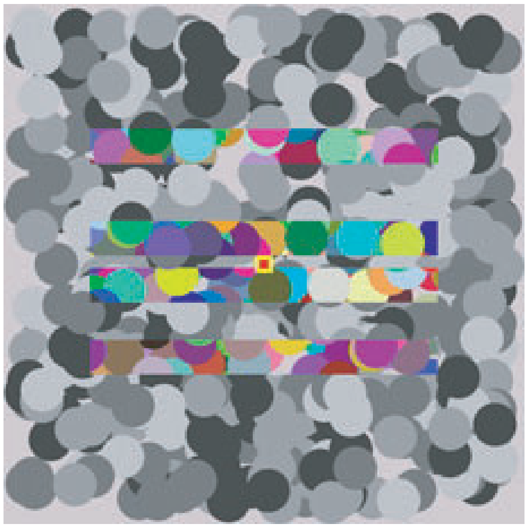

Figure 8. Movie of typical stimuli used in the false color conditions of Experiment 3.

Method

Observers

Eleven observers from the Visual Attention Laboratory's paid observer panel participated in this experiment.

Stimuli

Transparent and opaque stimuli were as described in Experiment 1a. False color stimuli were constructed by replacing the greenish filter transformation described in Experiment 1a with an algorithm that randomly assigned RGB values to the existing background dots.

Procedure

There were four blocked conditions: search for an opaque bar among transparent bars and vice versa, as well as search for a false colored opaque bar among false colored transparent bars and vice versa. The first two conditions were a replication of Experiment 1a and are reported in Tables 1 and 2. The order of conditions was counterbalanced across observers. There were four set sizes: 1, 2, 3, and 4 items. Methods were otherwise similar to previous experiments.

Results and discussion

Discarded fast and slow RTs constituted no more than 1% of any individual's data. Data for one observer were excluded for violating the error criterion. Figure 9 shows the mean correct RTs as a function of display size for both target present and target absent trials for the remaining 10 observers. Error rates are shown in Table 4 and reflect the pattern of errors obtained in Experiment 2.

It is clear from Figure 9 that the efficiency of search is adversely affected by changing the items from simulations of a physically plausible filter to simulations of an impossible filter. Note that all of the motion cues (relative and absolute) and all of the form cues (T-junctions vs. X-junctions) are identical in the plausible filter and false color conditions. These motion and form cues are not *sufficient* to produce the relatively efficient search for opaque targets among transparent distractors, though our pilot experiments suggested that motion cues might be *necessary*. Experiments 2 and 3 suggest that neither absolute nor relative motion cues that differentiate transparency from opacity are sufficient to guide attention.

Experiment 4: Impossible filters with possible luminance statistics

Perhaps the false color filter of Experiment 3 is too dramatic. A transparent surface produces both local (dot by dot) and global (whole surface) changes in luminance and chromatic statistics. The false color transformation made radical changes in the global statistics. Suppose we

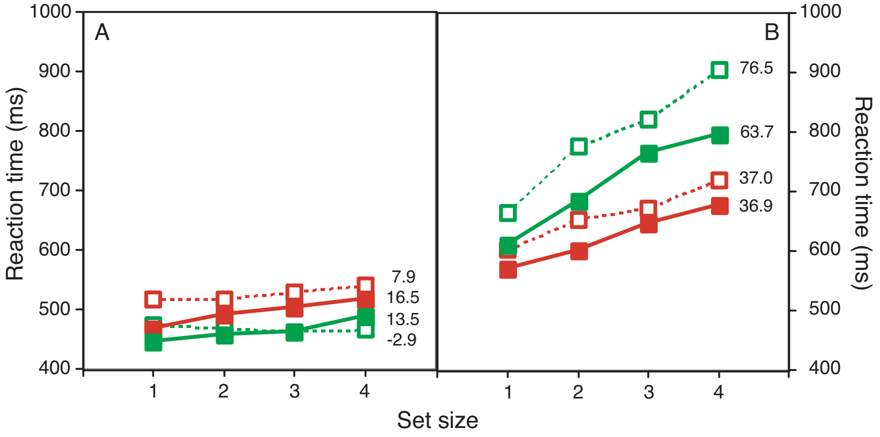

Figure 9. RT x set size functions for search for opaque among transparent stimuli (green symbols) and vice versa (red symbols). Solid lines and symbols are target present data; dashed lines and hollow symbols are target absent. Slopes are given to the right of the data. The plausible filter cases (Panel A) are a replication of Experiment 1a, showing an advantage for the opaque targets. From top to bottom, slopes are given in this order: transparent absent, transparent present, opaque present, and opaque absent. In the false color conditions (Panel B), the items have colors inconsistent with any physically transparent filter. The asymmetry reverses and search becomes markedly slower and less efficient.

Item colors	Plausible		FALSE		Plausible		FALSE	
Target type	Opaque	Transparent	Opaque	Transparent	Opaque	Transparent	Opaque	Transparent
Set size	MISS % (target present)				FA % (target absent)			
1	4.5%	2.5%	5.2%	8.1%	4.5%	5.1%	5.0%	2.7%
2	3.9%	5.4%	8.3%	8.4%	2.3%	2.2%	4.6%	4.1%
3	7.2%	7.7%	15.9%	9.6%	2.3%	2.2%	5.1%	3.4%
4	9.7%	9.8%	14.0%	9.6%	1.7%	2.7%	5.1%	3.8%

Table 4. Error rates for Experiment 3. FA = false alarm.

preserved the global distribution of color and luminance created by the greenish filter of Experiment 1 but mapped the specific local colors onto the wrong dots (Figure 10). This amounts to preserving overall Michelson contrast, which has been suggested as an important cue in transparency perception (Singh & Anderson, 2002). Consider two background dots, A and B. Under the plausible transparent transformation of Experiment 1, A would be transformed to f(A) as it passed under the filter and B to f(B). Would the ability to search for the opaque target among transparent distractors be preserved if we mapped, for example, A to f(B) and B to f(A)?

Method

Observers

Seventeen observers from the Visual Attention Laboratory's paid observer panel participated in this experiment.

Stimuli

The stimuli were similar to those used in Experiment 1a. Opaque and transparent bars were created as before. False transparent bars were created by generating a background having the same spatial layout as the actual background but with randomly scrambled grayscale values. This alternate background was filtered to produce the substrate for the falsely transparent items. These items had the same average luminance, contrast, and chrominance values as the transparent item. When they moved over the background, the motion internal to the item was the same in false and true transparent items. The cues to the falseness of the transparency would be impossible luminance transitions across the borders (e.g., one spot getting brighter and a neighboring spot of the same color getting dimmer). The impossible transitions also generate X-junctions that violate the physical constraints on junctions formed by contours crossing filter boundaries (e.g., Adelson & Anandan, 1990; Beck & Ivry, 1988; Metelli, 1974).

Procedure

Each observer was tested in two pairs of conditions. In one pair, false transparent stimuli were pitted against opaque stimuli. In the other, false transparent were pitted against transparent. Set sizes were 1, 2, 3, and 4. Observers were tested for 40 practice and 300 experimental trials in each condition. Order of conditions was counterbalanced across observers.

Results and discussion

Discarded fast and slow RTs constituted no more than 1% of any individual's data. RT x set size functions are shown in Figure 11. Beginning with Panel A, it is clear that search for the false transparent items among opaque items and vice versa was not efficient, certainly not as efficient as the comparable conditions of Experiment 1. In contrast, Panel B shows that the false transparent item behaved much like an opaque item. It was found with relative ease among truly transparent distractors (slope of 12 ms/item on target present trials). Moreover, we see the now-familiar asymmetry. Search for the transparent target among falsely transparent distractors was less efficient (31 ms/item), though it was still a faster search than the searches for opaque among false transparent (37 ms/item). Error rates were unremarkable. Misses averaged 8-9% for the false transparent/opaque searches and 5-6% for the false transparent/transparent searches.

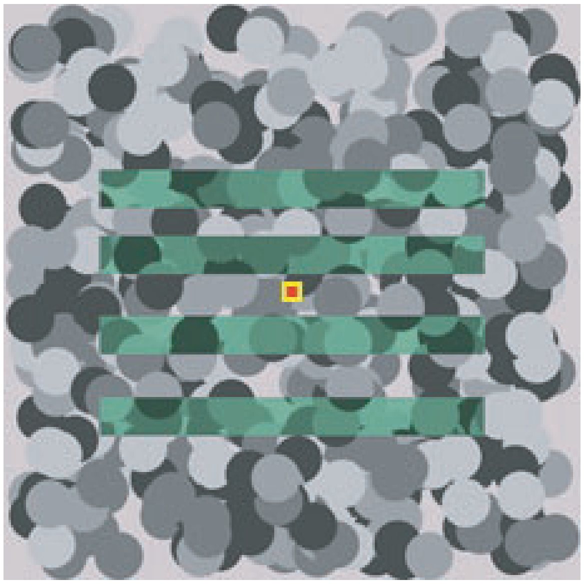

Figure 10. Movie of typical stimuli used in Experiment 4: a search for an opaque target among *false transparent* distractors. Note that X-junctions persist with these falsely transparent stimuli.

In this experiment, the false transparent items had the figural properties (X-junctions vs. T-junctions), the movement properties, and the average luminance properties of truly transparent items. Only the local luminance values provided information that contradicted the hypothesis of a transparent filter. However, this violation was enough to cause the false transparent items to be treated as if they were opaque. Apparently, they are quite confusable with opaque items, and easier to discriminate from transparent items in search tasks. Thus we see that, at least for our stimuli, motion cues are necessary (pilot data) but not sufficient (Experiment 2, 3, and this experiment). The same is true for the luminance cues: The correct local luminance cues are necessary (Experiment 3 and this experiment) but not sufficient (luminance cues were present in the pilot experiments with stationary stimuli). In the remaining experiments, we turn to the form cues–the junctions formed as contours cross the filter boundary and the accretion and deletion of contour information at opaque boundaries.

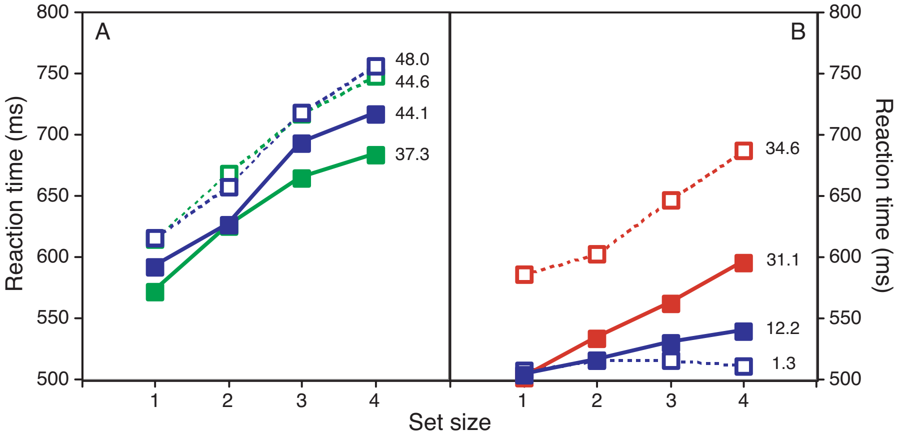

Figure 11. A. RT x set size functions for search for *false transparent* items among opaque stimuli (blue symbols) and opaque targets among *false transparent* distractors (green symbols). Solid lines and symbols are target present data; dashed lines and hollow symbols are target absent. Slopes are given to the right of the data. B. RT x set size functions for search for *false transparent* items among transparent stimuli (blue symbols) and transparent targets among *false transparent* distractors (red symbols). Solid lines and symbols are target present data; dashed lines and hollow symbols are target absent. Slopes are given to the right of the data

Experiment 5: Are the figural cues necessary?

A transparent filter produces X-junctions as contours in the background pass under the filter. An opaque item produces T-junctions when the contours in the background are occluded by the overlying surface. Experiments 3 and 4 showed that the mere presence of this junction distinction is not sufficient to produce the relatively efficient searches of Experiment 1. Are these junctions necessary at all?

Method

Observers

Twelve observers from the Visual Attention Laboratory's paid observer panel participated in this experiment.

Stimuli

Opaque bars were constructed as before. Here we introduce a new type of false transparency. In this experiment, a false transparent item was created by taking a transparent item from one location and placing it in the incorrect position in the field. Thus, like a transparent item, contours were accreting and deleting within the falsely transparent bar. This preserves the motion and the global luminance statistics within the falsely transparent item. However, this manipulation eliminates item continuity across the filter border. Non-accidental X-junctions have been eliminated and T-junctions predominate. Sample stimuli are shown in Figure 12.

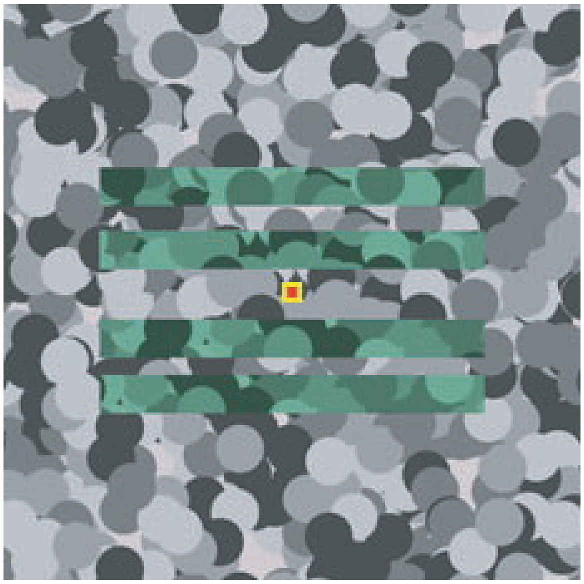

Figure 12. Movie of typical stimuli used in Experiment 5. A search for an opaque target among *false transparent* distractors. Note that these falsely transparent items form T-junctions with the background contours.

Procedure

Observers were tested on searches for an opaque bar among false transparent bars and vice versa. These were blocked conditions consisting of 40 practice trials and 300 test trials. The conditions were counterbalanced across observers. There were four set sizes: 1, 2, 3, and 4 items. All other aspects of the experiment were similar to previous experiments.

Results and discussion

Discarded RTs constituted no more than 1% of any individual's data. Figure 13 shows the mean correct RTs as a function of display size for both target present and target absent trials. Table 5 displays the error rates.

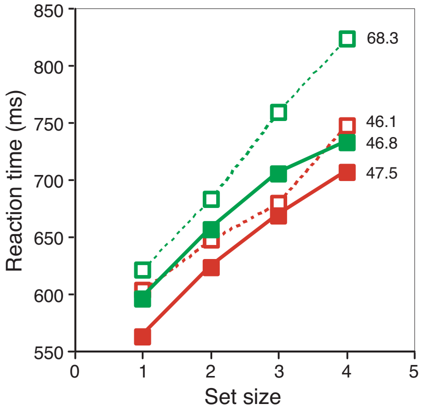

Figure 13. RT x set size functions for search for opaque among *false transparent* stimuli (green symbols) and vice versa (red symbols). Solid lines and symbols are target present data; dashed lines and hollow symbols are target absent. Slopes are given to the right of the data. In this experiment, the *false transparent* items were taken from a piece of background that did not lie under the putative filter so that while the contours moved like those beneath a transparent filter, contours in the background were not completed across the filter boundary.

Again the results of the manipulation are obvious. The search is markedly inefficient. Note that these stimuli had the same motion and global luminance cues as the stimuli of Experiment 1. This suggests that the X-junctions are necessary to support the good performance seen in Experiment 1, and their absence can account for poor performance not only here but also in Experiment 2. Like motion and luminance cues, form cues to transparency/opacity appear to be necessary but not sufficient.

How necessary are those X-junctions? Is it important that explicit X-junctions be present in the display or is it enough to have the same contours appearing in the background filtered or unfiltered? Can we hide the actual point of intersection? That is the next question.

Experiment 6: Good continuation stimuli

Experiment 5 showed that performance is impaired when X-junctions are removed from the transparent items. What happens if they are merely hidden? In Experiment 6, a frame was placed around each item.

Method

Observers

Fourteen observers from the Visual Attention Laboratory's paid observer panel participated in this experiment.

Stimuli

In the framed conditions, a 0.2° thick frame was placed around each search item as shown in Figure 14. It was colored a mid-level green (6.2 cd/m^2, CIE coordinates: $x = 0.272$, $y = 0.385$). Stimuli were otherwise similar to the previous experiments.

Target type	Opaque	False transparent	Opaque	False transparent
Target presence	Present		Absent	
Set size	MISS %		FA %	
1	4.8%	6.3%	4.0%	4.0%
2	6.2%	3.7%	4.1%	5.0%
3	7.2%	8.6%	4.0%	2.9%
4	13.3%	12.9%	5.3%	4.6%

Table 5. Error rates for Experiment 5. FA = false alarm.

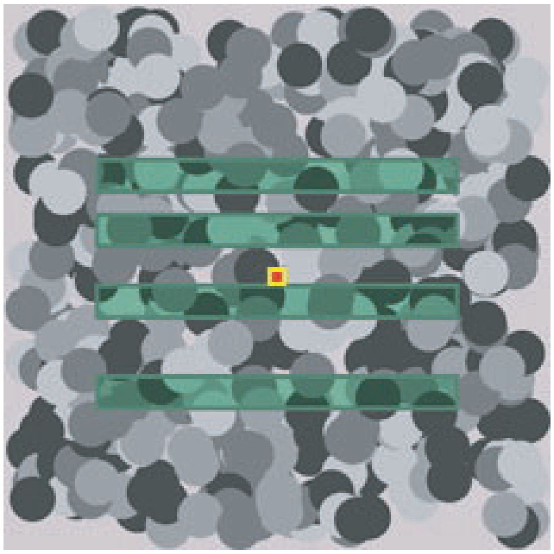

Figure 14. Movie of typical stimuli used in the frame conditions of Experiment 6. Placing frames around each item makes T-junctions out of all explicit points of contact between the search items and the background. In the transparent items, however, contours can be seen to complete behind the frame.

Procedure

Observers were tested in four blocked conditions: search for an opaque bar among transparent bars and vice versa without frames, search for an opaque bar among transparent bars and vice versa with frames. In the no frame conditions, the stimuli were the same as those used in Experiment 1a and are reported in Tables 1 and 2. Each condition consisted of 40 practice trials and 300 test trials. The order of conditions was counterbalanced across observers. There were four set sizes: 1, 2, 3, and 4 items.

Results and discussion

Discarded fast and slow RTs constituted no more than 1% of any individual's data. RT x set size functions for the no frame and frame conditions are shown in Figure 15.

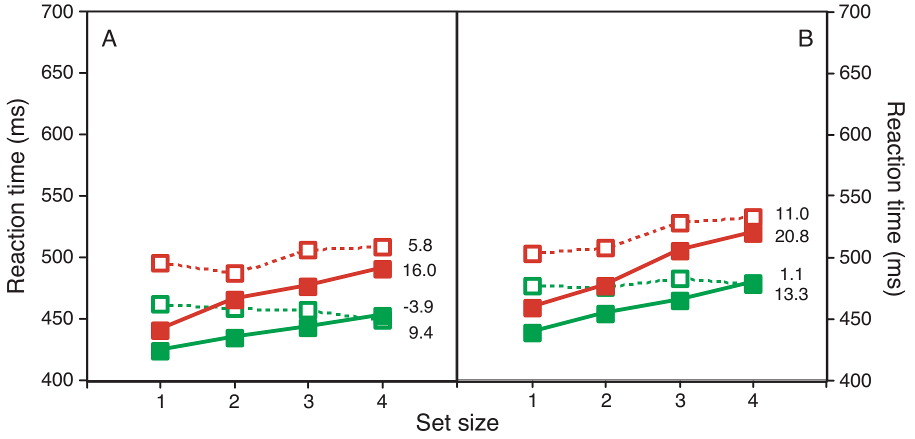

Figure 15. RT x set size functions for search for opaque among transparent stimuli (green symbols) and vice versa (red symbols). Solid lines/symbols are target present data; dashed lines and hollow symbols are target absent. Slopes are given to the right of the data. The no frame cases (Panel A) are a replication of Experiment 1a, showing an advantage for the opaque targets. In the frame conditions (Panel B), each item has a frame around it to eliminate explicit X-junctions. However, contours can be traced in their path behind the frame (good continuation).

Unlike eliminating the X-junctions, hiding the X-junctions produces only modest effects in this experiment, consistent with similarly weak effects in transparency perception with comparable manipulations (Kasrai & Kingdom, 2002). Looking at the target present trials, there is a main effect of adding a frame, $F(1,13) = 5.9$, $p < .05$, reflecting a slight slowing of RT in the frame conditions. The frames do not significantly increase slopes for either opaque targets, $t(13) = 1.5$, $p = ns$, or transparent targets, $t(13) = 1.6$, $p = ns$, relative to the corresponding no frame conditions. The advantage for opaque targets is seen again. The main effect of target type is significant, $F(1,13) = 10.4$, $p < .05$, and the slopes for transparent targets are steeper both with a frame, $t(13) = 2.5$, $p < .05$, and without a frame, $t(13)= 3.7$, $p < .01$, compared to the slopes for opaque targets.

Miss errors average 8% in this experiment. They increase with set size but are not influenced by the frame/no frame manipulation.

These results suggest that the figural rules that allow contours to complete under a narrow occluder are at work here as they are in other visual search tasks (Rensink & Enns, 1998). In combination with the cues from the motion of the stimulus, these contours provide enough information for the system to infer the opacity or transparency of items and to permit relatively efficient search for opaque targets among transparent distractors.

Experiment 7:
Is good continuation needed?

In Experiment 6, background contours could be traced under the occluding frame of a transparent item. In Experiment 7, we used a background texture made of much smaller dots. Individual dots were completely occluded as they passed under the frame in the transparent case. Thus, dot contours could not be traced. In the absence of such contours, transparency would have to be inferred from the disappearance and reappearance of the same dots on either side of the frame and/or from the bridging of the frame by larger structures in the image–clusters of dots and/or low spatial frequency information.

Methods

Observers

Twelve observers performed the frame and no background conditions. A different set of 15 observers performed the no frame control conditions. All observers were from the Visual Attention Laboratory's paid observer panel.

Stimuli

There were six conditions in Experiment 7. In all cases, the background was composed of dots 0.2° in width, one tenth the diameter of the larger dots used thus far. A dot of this size would be entirely occluded as it passed behind a 0.2° frame identical to that in the previous experiment. Dot number was increased 100-fold (50,000 dots) to produce continuous background textures.

The no frame conditions were replications of the standard search for opaque among transparent and transparent among opaque conditions of the prior experiments using these smaller dots. The frame conditions were replications of the frame conditions from the prior experiment but with the smaller dots. To check on the role of motion cues with these smaller dots, no background conditions were also tested. These were replications of the no background conditions of Experiment 2 with the smaller dots. Other aspects of the methods were similar to the previous experiments.

Procedure

Each condition consisted of 40 practice trials and 300 test trials. The order of conditions was counterbalanced across observers. There were four set sizes: 1, 2, 3, and 4 items.

Results and discussion

Discarded fast and slow RTs constituted no more than 1% of any individual's data. Data for two observers were excluded for violating the error criterion. Figure 16 shows the correct RT x set size functions for all conditions in this experiment.

It is obvious that, as in Experiment 2, the no background conditions are markedly worse than the conditions with a background. We can conclude that the motion cues are not sufficient with small dot stimuli, as they were not sufficient with the large dots of Experiment 2.

The comparison of interest in Experiment 7 is the comparison between frame and no frame conditions. Search for opaque targets is somewhat less efficient in the frame (15.4 ms/item) than in the no frame (7.4 ms/item) case but unpaired *t* tests reveal this difference to be only marginally significant, $t(23)= 1.8$, $p = .088$. There is no reliable difference in search for transparent targets (frame: 14.8 ms/item, no frame: 15.7 ms/item). Unpaired *t* tests on the RTs reveal no significant differences between frame and no frame RTs at any set size [all $t(23) < 1.0$, all p = *ns*]. Both frame and no frame conditions replicate the asymmetry showing faster responses to opaque targets [frame: $F(1,10) = 11.4$, $p < .01$; no frame: $F(1,13)= 23.8$, $p < .01$].

There are no notable trends in the error data except that errors in the no background conditions are somewhat higher (10%) than in the frame and no frame conditions (6%).

The results from this experiment show that it is not necessary to be able to see a clear contour running beneath an occluder in the frame conditions. When there is adequate information for the visual system to infer that the texture seen inside the bar is reappearing after passing behind the frame, the visual system is able to treat these bars as different from opaque bars. This experiment adds to the evidence that, given sufficient information, search for opaque targets is quite efficient and more efficient than search for transparent objects.

The frame experiments also show that mere presence of accretion and deletion information is not the critical cue in search for opaque among transparent items. Moving opaque stimuli are marked by the deletion of background contours at the leading edge of the opaque bar and by the accretion of background contours beyond the trailing edge. This accretion and deletion does not occur for transparent stimuli *without frames*. However, once frames are added, some accretion and deletion is present for both transparent and opaque stimuli, though the exact pattern is different. If the defining cue for an opaque bar had been mere accretion/deletion, we would have expected the addition of a frame to be more damaging that it was. In effect, accretion and deletion would have made the transparent stimulus more like an opaque stimulus for purposes of guidance. The modest effect of that frame indicates that this was not the case.

Conclusions

The experimental results presented here suggest that attention can be guided to the opaque object among transparent distractors. Moreover, it seems to be easy to decide that all items in a display are transparent. Target absent responses are very efficient in search for opaque among transparent. It is more difficult to find one transparent item or to determine that all items are opaque. In the standard analysis of search results (Wolfe & Horowitz, 2004), this would suggest that opacity is the "feature" and that transparency is the absence of opacity.

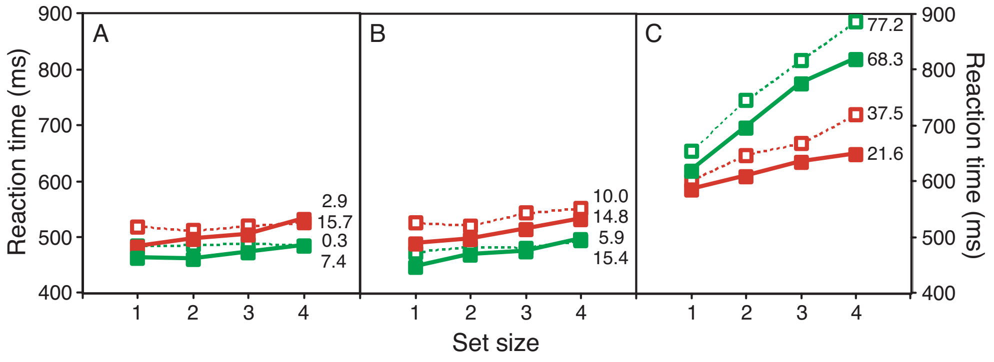

Figure 16. RT x set size functions for search for opaque among transparent stimuli (green symbols) and vice versa (red symbols). Solid lines and symbols are target present data; dashed lines and hollow symbols are target absent. Stimuli are composed of small dots. The no frame conditions (Panel A) are similar to Experiment 1a. The frame conditions (Panel B) are similar to Experiment 6, except now items have frames with width equal to dot size, eliminating contour completion. The no background conditions (Panel C) are similar to Experiment 2. Slopes are given to the right of the data.

However, the case of opacity and transparency may be more interesting than the usual analysis of a guiding feature. Targets defined by a typical feature such as color, size, or motion are defined by a single irreducible cue. Even in the case of higher order attributes like depth cues (Enns & Rensink, 1991), search is driven by a single cue, and the control experiments exist to show that efficient search for a target based on a depth cue is not actually search for something like a shape cue or a size cue.

Transparency and opacity, in contrast, may be the first–or, at least, the clearest–example of guidance by cue combination (Landy et al., 1995). Forthcoming work on shadows might fall into a similar category (Rensink & Cavanagh, in press). In the real world, we continually combine cues from a wide range of sources to make our best guess about the nature of the stimulus giving rise to those cues. Many current theories suggest that we use a Bayesian framework to evaluate these cues in the light of prior knowledge, innate and learned (Ernst & Bulthoff, 2004; Kersten, Mamassian, & Yuille, 2004). Multiple cues give rise to the impression of a transparent or opaque surface. The results of our experiments indicate that the visual system is not relying on any single source of information. Instead, it is combining motion, luminance, and figural cues to make a case for the transparency or opacity of an object. If any of the cues is compromised, the system appears to default to the hypothesis that an opaque object is present. For example, in Experiments 3 and 4, the luminance values violate the rules of transparency. Even though other cues point to transparency and even though the falsely transparent stimuli can look quite transparent when scrutinized, search becomes inefficient as if the incorrect luminance information vetoed the other cues.

It is also possible for a cue to have an effect by its absence. In the pilot experiments, we failed to find efficient search for stationary opaque or transparent items. Unlike the false luminance values, nothing about a stationary item violated the physics of transparency. Instead, we may need motion to create a transparent versus opaque signal that is great enough to allow efficient search. Experiments 2-5 show that it is not the motion cue alone that supports the efficient search for opaque targets. Rather, motion is part of the combination of cues that make a sufficiently strong guiding signal.

The present data do not permit us to determine the exact rules of cue combination in this case. With other attributes (e.g., orientation), the guiding attribute has different properties than the attribute perceived once an item is selected. Thus, for example, guidance by orientation is coarse (Foster & Ward, 1991) and categorical (Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992), while the perception of orientation is not. In the case of transparency/opacity, we do not know if the rules of cue combination for guidance are the same as those for perception.

Why is search for opacity more efficient than the search for transparency? Perhaps this represents a sensible choice on the part of the visual system. A moving opaque object is an object and might be worth selecting for further processing. What can be interpreted as a moving transmissive medium may not actually be an object at all. For example, a moving shadow would have properties very similar to our moving filters. In the real world, a moving shadow might not have much claim on our attention.

Of course, the framed transparent items of Experiments 6-7 were "objects" just as surely as the framed opaque items, and the preference for opaque remains. However, a preference is just a preference, not an absolute rule. One can imagine that, all else being equal, one would do better to attend to a solid item in motion than to what might only be its shadow.

In summary, the present data show that search for opacity, in particular, is efficient and is not reducible to simpler component cues like motion, luminance distributions, or junction type. It remains to be seen if transparency/opacity is just one example of a much larger set of instances of guidance by cue combination. Many other surface properties (e.g., shininess or wetness) could lend themselves to the sort of analysis described here.

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Footnotes

[1] In the interest of improving the flow of the manuscript, we have omitted reporting statistics in those cases where the effects are large and immediately obvious from a glance at the data. The differences, in these cases, were always reliable at a level of $p < .01$. Statistics are reported for subtler points.

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