The Effect of Transparency on Recognition of Overlapping Objects

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Abstract

Are overlapping objects easier to recognize when the objects are transparent or opaque? It is important to know whether the transparency of X-ray images of luggage contributes to the difficulty in searching those images for targets. Transparency provides extra information about objects that would normally be occluded but creates potentially ambiguous depth relations at the region of overlap. Two experiments investigated the threshold durations at which adult participants could accurately name pairs of overlapping objects that were opaque or transparent. In Experiment 1, the transparent displays included monocular cues to relative depth. Recognition of the back object was possible at shorter durations for transparent displays than for opaque displays. In Experiment 2, the transparent displays had no monocular depth cues. ; there was no difference in the duration at which the back object was recognized across transparent and opaque displays. The results of the two experiments suggest that transparent displays, even though less familiar than opaque displays, do not make object recognition more difficult, and possibly show a benefit. These findings call into question the importance of edge junctions in object recognition.

KEYWORDS: object recognition, transparency, occlusion, perception

The Effect of Transparency on Recognition of Overlapping Objects

Human object recognition is a complex process that has been investigated for many years, but its mechanisms are still being debated (DiCarlo & Cox, 2007; Hayward, 2003). The increasing reliance of humans on technology to assist in complex visual tasks means that humans engaged in work such as security image inspection or medical image inspection are now using unnatural presentations of objects to try to identify the objects. Although technology improvesthe efficiency of task performance, it introduces challenges to the human visual system.

One example of an unnatural feature of X-ray images of luggage is that objects are presented as transparent, which removes some of the normal cues to object identity such as junction information at point of overlap. X-ray images of objects are artificial in that they have unnatural colors, surface features, depth relationships and opacity. Past research has shown that although object recognition is robust enough to survive many changes in visual features, it can degrade due to changes in the expected color, texture, and reflectance of objects (Humphrey, Goodale, Jakobson & Servos, 1994; Tanaka, Weiskopf & Williams, 2001). When such changes are added to the clutter in the displays and uncertainty about what the target will look like, object recognition becomes quite difficult (McCarley, Kramer, Wickens, Vidoni, & Boot, 2004). Some people develop skill at using X-ray images in security settings whereas others do not, which suggests that something about the displays requires a new skill (Fiore, Scielzo & Jentsch, 2004).

The artificiality of X-ray images is likely to contribute to the difficulty of detecting weapons in packages and luggage. It is important to test the robustness of object recognition in the face of changes in visual characteristics. This paper presents research aimed at exploring how people cope with changes to the apparent transparency of objects. In this research we look for differences in the minimum inspection time that people need to identify overlapping objects when the objects are either transparent or opaque.

Recognizing Overlapping Objects

What is the process by which occluded or transparent objects are recognized? The external contour is the primary determinant of the subjective representation of the shape of an object. According to most theories, object recognition is achieved through the following steps: (1) edges are found, (2) regions or volumes are identified based on joining edges, (3) figure/ground determination is made to clarify which regions are relevant to each object, (4) the arrangement or structure of the regions or volumes is determined, (5) surface features might or might not be added to those structures, and (6) the resulting structures are used to probe memories (e.g., Biederman, 1989; Palmer, 2003).When a single object appears in isolation, determining its shape in this manner is straightforward.

The ability to recognize overlapping occluded objects depends on three kinds of processes. The first two, boundary interpolation and surface completion, are required for the visual system to deduce the existence and nature of unseen features from visible, non-occluded information (Yin, Kellman & Shipley, 1997). These processes sometimes work over long distances to group two regions of visible but spatially separated contours and surfaces (e.g., Kellman, Yin & Shipley, 1998). The third process, parsing, is required to determine which parts belong to one object and which parts belong to the other (Rensink & Enns, 1998). Once the structure of an object is seen, parsing is based on boundaries: anything that is on one side of an important boundary belongs to one object; anything on the other side belongs to the other object. There is no consistent opinion in the field about whether parsing is purely a perceptual task or partly a cognitive task (e.g., Rock, 1987; Kanizsa, 1979).

In their discussion of overlapping, opaque displays, Nakayama, Shimojo and Silverman (1989) distinguish between intrinsic contours (those that truly represent the contours of the object) and extrinsic contours (those that appear to be part of the object border but actually represent the other object). At the point where one object occludes another, the contour at the region of occlusion is intrinsic to the occluding object and extrinsic to the occluded object. If the viewer is to recognize the occluded object accurately, he or she must discount extrinsic contours when deriving object-shape information. Nakayama et al. asserted that the perception of relative depth, whether acquired through binocular disparity or pictorial cues to depth, was necessary to assign a contour to be intrinsic to one of the regions it divided, and that perception of relative depth preceded recognition of the shapes of objects. They pointed out that when binocular depth cues are missing (as in 2-D pictures), monocular depth cues remain. In particular, the most fundamental cue to depth is the presence of t-junctions, which play a particularly important role in the perception of occlusion (N. Rubin, 2001). When one object extends behind another, its intrinsic edges tend to stop at the occlusion contour, and the occlusion contour is unbroken (see Figure 1). T-junctions rarely occur where there is no occlusion. It is important to note that Nakayama et al. did not consider a third class of contours in overlapping opaque objects – those that represent sharp changes in surface luminance, color or texture rather than shape, such as an edge arising from a shadow cast across an object. However, the regions on either side of such contours would not differ in depth discontinuously, and so the same depth processing that assigned occlusion-contours to the occluding surface would be able to discount the third class of contour in subsequent shape-based object recognition.

---------- Insert Figure 1 about here ----------

Because all the contours and surfaces of overlapping transparent objects are visible, recognizing such objects requires parsing but does not require boundary interpolation and surface completion. The parsing done for transparent overlap is more complex than that done for occluding overlap. For transparent overlap, contours again may be intrinsic, extrinsic or superficial to shape, but depth cues are a weaker diagnostic that a contour is extrinsic. In particular, because the front object is transparent, t-junctions are rare at the region of overlap (although there are special cases where they do occur, Watanabe & Cavanagh, 1993). Contours of the back object that in opaque overlap would end at the region of overlap continue to be visible through the front object in transparent overlap. Thus, at the point of overlap, opaque pictures would show t-junctions but transparent pictures would show x-junctions. X-junctions are important clues to transparency (Metelli, 1974; Kanizsa, 1979). T-junctions in opaque displays are strong indicators of relative depth, but x-junctions in transparent junctions are not necessarily informative about relative depth. Depth differences therefore are less useful in parsing overlapping transparent objects than in parsing overlapping opaque objects. The difference between opaque and transparent overlap in terms of the use of monocular depth cues to parse objects could become particularly important when binocular depth cues are missing. In our dynamic, three-dimensional world, binocular cues to depth abound. However, in pictures of overlapping transparent objects, and in particular in current X-ray images of luggage, there are no binocular depth cues. Thus, there is reason to suspect that object parsing and object recognition in X-ray images of luggage may be more difficult when the objects are transparent than when they are opaque.

The perception of transparency depends not only on the arrangement of contours but also on the arrangement of luminance and colors of the regions around the contours (Beck, Prazdny & Ivry, 1984; Metelli, 1974; Singh & Anderson, 2002). When the arrangement of luminance and colors does not follow principles that previous research has identified, observers are less likely to report perceiving transparency (D'Zmura, Colantoni, Knoblauch & Laget, 1997; Singh & Anderson, 2002). Thus surface features as well as contours contribute to the perception of transparency.

Time Course of Detection of Occlusion and Transparency

If there are differences in how well people can recognize of overlapping opaque and transparent objects, the differences might show up in the time-course of processing. To the best of our knowledge, no researchers have directly compared opaque and transparent object recognition. Studies using each kind of display separately have used quite different methodologies, making their results difficult to compare.

In an investigation of how rapidly transparency is seen, Watanabe and Cavanagh (1992) presented overlapping thickly printed digits that had the correct or incorrect arrangements of region luminances to support a perception of transparency. In one task, participants reported whether they perceived transparency and in another task participants identified all digits presented. Watanabe and Cavanagh showed that (a) there was a strong correlation between the perception of transparency and the accuracy of digit identification, (b) there was a higher likelihood of reporting the perception of transparency in displays that used correct rather than incorrect luminance patterns, (c) transparency was correctly perceived as long as the presentation time was at least 60 ms, and (d) object recognition in transparent overlap displays continued to improve through 150 ms, which was the longest presentation time tested.

Recognition of occlusion is also rapid, but the time-course of detecting occlusion has not been directly studied. The time-course of *recognizing* occluded objects was investigated in a study examining priming from occluded shapes (Sekuler & Palmer, 1992). The study showed that an occluded object primed its completed shape if the prime duration was at least 200-400 ms, but not if the prime duration was 50-100 ms. Further, the study showed that priming from a non-overlapped shape develops earlier than priming from an overlapped shape, by 100 ms.

The recognition of occlusion may not be instantaneous, but it occurs automatically, without focal attention (Rensink & Enns, 1988). When participants searched for a circle partially occluding a square amid circles and squares that were separated in space and reported whether it was present or absent, search for the target was effortful. In a separate condition, the target contained the same shapes (circle next to a square with a corner missing) but with space between the two shapes. With this alteration, search required only 7 ms per element and absent responses were just as fast. The difference in response time for the two display conditions suggests that there was a very fast determination that the square with a corner missing either was the full object that was not occluded or was an ordinary square that was occluded. The squares with corners missing popped out preattentively from square and circle non-targets because the deformed square was unique, whereas the squares occluded by circles did not because there were other squares in the display.

Indirect Clues that Opaque and Transparent Object Recognition may be Different

In our day to day interactions, we experience overlap of both transparent and non-transparent objects but because most objects are not transparent, overlap normally results in partial occlusion of one object by another. The visual system tends to interpret ambiguous stimuli according to which interpretation is more probable (Gregory, 1997), The relationship of t-junctions to occlusion and x-junctions to transparency is somewhat ambiguous; accidental viewpoints and shape-irrelevant surface features can lead to t-junctions at regions of transparency and x-junctions at regions of occlusion, although the other relationship is more probable. Because partially occluding overlap is more common than transparent overlap in natural and man-made environments, one might assume that the visual system has a default bias to interpret t-junctions as representing overlap and x-junctions as representing abutting surface features such as surface color patterns as often as representing transparent overlap. It follows, then, that people would recognize objects that are transparently overlapped more slowly or with more effort than they would recognize objects that overlap with partial occlusion. If it take 30-60 ms to recognize that an object is transparent (Watanabe & Cavanagh, 1992), and if the system is biased to assume that surfaces are opaque, then the first 30-60 ms of viewing time might be of more benefit to recognizing opaque objects than transparent objects. Alternatively, if the visual system is not biased, or if the visual system can efficiently use the extra information available in transparent displays about the contours and surface of the overlapped object, there may be no difference in how easily people can recognize transparent and opaque overlapping objects.

To further bolster the argument that object recognition may be different for transparent and opaque objects, it is worth looking at differences not just in typical adults but also in typical infants and in neurologically impaired adults. Here, too, there are suggestions that there may be differences between recognition of transparent and opaque objects. Recognition of simple occluded objects is possible by 4 months of age (Needham & Baillargeon, 1997). Although transparency can also be processed by four months of age (Otsuka, Kanazawa & Yamaguchi, 2006), the perception of transparency appears to be less robust than the perception of occlusion at least until seven months (Johnson & Aslin, 2000; Kellman & Spelke, 1983). Therefore, the ability to parse objects based on transparency is likely to develop somewhat more slowly and possibly differently from the ability to parse objects based on occlusion. In adults with neurological injury, too, there appears to be a difference, and possibly even a double dissociation, between impairment in transparent object recognition and impairment in occluded object recognition. Visual agnosia can result in greater difficulty in recognizing objects in overlapping line drawings compared to non-overlapping line drawings (Humphreys & Price, 1994), but at least one agnosic (HJA) has been shown to be slower at recognizing occluded geometric shapes in line drawings than the same shapes in superimposed line drawings (Giersch, Humphreys, Boucart & Kovács, 2000). The differences between transparent and opaque object recognition in infancy and with agnosia do not in themselves strongly motivate the research presented here, but they hint at the possibility of finding differences between recognition of transparent and opaque objects in neurologically intact adults.

If there are differences in recognition of opaque overlapping objects and transparent overlapping objects, as the evidence discussed in the preceding paragraphs indicates, the differences could be due to either of two possibilities. One possibility is that independent component processes may be involved in opaque and transparent recognition (a strong claim). An alternative possibility is that the difference could be more quantitative in nature, due to the more efficient processing of one stimulus type (opaque objects) and the less efficient processing of another stimulus type (transparent objects). All evidence to date points to efficiency differences in the recognition of opaque and transparent objects; none of it strongly supports a claim of independent component processes for the two kinds of processes. Therefore, the study presented here is aimed at finding only an efficiency difference.

The Current Study

To test whether the recognition of transparent overlapping objects is less efficient than the recognition of opaque overlapping objects, we adopted a method that focuses on measuring the limits of recognition. Specifically, we looked for the minimum time a picture of overlapping objects must be presented in order for a viewer to recognize the objects in the picture. Some pictures showed overlapping transparent objects; other pictures showed overlapping opaque objects. The threshold display durations in the two display conditions were compared. Measuring perceptual thresholds has been used successfully in the past to identify characteristics that affect object recognition (Dent, Catling & Johnston, 2007; Panis & Wagemans, 2009). Given that less relative depth information is available in transparent displays than in opaque displays, we predicted that object recognition would be faster with opaque displays than with transparent displays.

Experiment 1

Method

Participants. In total, 48 university students and staff from the University of Portsmouth participated in the study (11 male and 37 female). Mean age was 21.9 years, ranging from 18 to 51. Each participant received either partial course credit or £5 for participating. Eighteen participants were assigned to see opaque overlap displays, and 15 were assigned to each of the other two image types (transparent overlap and non-overlap). All participants reported good vision either naturally or with the lenses they were wearing. More participants were included in the opaque condition than in the other conditions because we expected not to be able to use some of their data.

Apparatus. A DELL Optiplex computer with a 19” ViewSonic G96B color monitor was used to present the stimuli. The software that controlled stimulus presentation was ePrime 1.2 (Schneider, Eschman, & Zuccolotto, 2002). Responses of participants were verbal, with the experimenter typing codes for the responses using the computer’s keyboard.

Stimuli. The original image of each object used for this study showed the object against a white background. The original images were provided courtesy of Michael J. Tarr, Brown University (http://www.tarrlab.org/). The image was not a photograph, but was a 24-bit color image created from a 3-D model of the object. All objects were nameable by the participants (as reported in the results). Some were very easy to recognize. Others were presented from unusual viewpoints (e.g., a tape dispenser viewed from above), and so were not as easy to recognize.

Defining "unusual" conservatively, so that the viewpoint had to be quite unusual to be counted, there were 8 objects presented in an unusual orientation. These images were merged into pictures showing pairs of objects using ADOBE Photoshop software. In total, 48 pairs of objects were set up, with each object appearing in only one pairing.

Three images were created for each object pair. There was one image for each image type, where the image types were overlapping transparent, overlapping opaque, and non-overlapping opaque. The criterion for deciding how much the objects would overlap was to ensure that the partly occluded object in the opaque condition would have enough identifying features visible that it could be recognized.[1] Overlapping transparent objects were created by making each object 75% opaque in Photoshop and then overlapping the images using "normal" layer mixing. This amount of opacity was chosen based on a subjective impression that the images looked transparent and not particularly pale. There was no objective technical reason for the choice. The "normal" mixing algorithm in Photoshop leaves some evidence of which object is in front. The makers of Photoshop do not provide information about how the image blending is done, but the monocular depth cues we could see were color-related.[2] The color of the front object appeared closer to the image's unlayered color than the color of the back object (when testing the mixing, we found this to be the case even when opacity was set to 50%). There were no apparent changes to the sharpness of the edges of the objects and no cast shadows. Overlapping opaque objects were created by first overlapping the 100% opaque images in Photoshop in exactly the same configuration as in the transparent overlap condition, and then making the resulting image 75% opaque. The manipulation of opacity did not make the objects look transparent, but matched the overall brightness and color saturation that was seen in the transparent overlap condition.

Non-overlap objects were created by making the two individual images 75% opaque and then placing them side by side in one picture. The object appearing on the left was chosen arbitrarily rather than systematically. Objects were at least 1° of visual angle apart. Non-overlap displays were therefore wider than overlapping displays.

A masking image was created by assembling small parts of all the object images in random and overlapping positions and adding some spots of color. The resulting image was saved in four orientations. For each image pair, one of the four orientations of the mask was assigned to be used whenever that image pair was presented.

Procedure. Participants were instructed to name the two objects in each picture. They were told that the first presentations of the pictures would be so brief that recognition would be unlikely, but that over the course of the experiment the pictures would be presented for progressively longer durations until most objects could be recognized. They were told that they were free to guess, but that it would be preferred if their guesses were based on what they had seen, and not on reasoning processes.

In the first cycle of pictures, each picture was presented for 100 ms. For the next cycle, each picture was presented for 117 ms, and for each subsequent cycle display duration progressively increased by 17 ms. Each picture presentation was preceded and followed by presentation of its mask displayed for 250 ms. See Figure 2 for a representation of the progression of a trial.

(Put Figure 2 approximately here.)

For each image the participant named any object they could recognize. The experimenter entered a code for each object indicating whether or not the participant had recognized it. If the participant named both objects correctly, the experimenter let them know they had done so. No feedback was given if one or both responses were incorrect. If the participant named both objects correctly, the image was dropped from the set during the next cycle. Thus, the number of object pairs presented in a cycle reduced as the experiment progressed. Object pairs were presented in random order in each cycle. The data collection phase of the study ended after 35 minutes.

Results

Table 1 shows the range of recognition performance by participants and the range of recognizability of objects used in the experiment. Because the experimenter noticed that some participants in the opaque condition were having an unusual amount of difficulty, we decided to remove data from any participant who recognized fewer object pairs than was two standard deviations below mean accuracy for his or her display condition. As a result, one participant was removed from the opaque overlap condition (accuracy of 4.2% compared to a mean of 56.7% and a standard deviation of 22.0%) and no participants were removed from the remaining two conditions (for transparent overlap, the mean was 67.1% and the standard deviation was 15.2%; for non-overlap, the mean was 79.9% and the standard deviation was 10.1%).

Because data collection occurred over fixed time of 35 minutes, different participants reached different display durations by the end of the session. The median final display duration was 262 ms, ranging from 168 to 492 ms.

Figure 3 shows the cumulative number of object pairs recognized at each duration up to 236 msec, averaged across participants.[3] There is no obvious difference in recognition between the transparent and opaque overlap displays. Recognition of overlapping objects required more time than recognitition of non-overlapping objects.

(Put Figure 3 approximately here.)

To analyze recognition accuracy, a stepwise Cox regression survival analysis was run with the non-survival time of an object pair defined as the duration at which both objects were recognized. Cox regression survival analysis is used to model the distribution of times until an event occurs and to evaluate what factors influence the time until the event occurs. The term "survival" is used because the most common early applications of the technique were to medical studies of the epidemiology and influence of treatment factors on disease (Fox, 2002). However, the method is appropriate for analysis of "time until event" for events other than death. In our study the event of interest is recognition, and so "survival" is equivalent to "not yet recognized" and "non-survival" is "being recognized". An excellent example of a previous use of survival analysis in perception research is work by Panis and Wagemans (2009).

For the current study, survival analysis is a more appropriate technique than an ANOVA of the effect of display duration on recognition because a substantial number of objects were never recognized and because there was variability in the display duration reached by the end of an experimental session. Thus, at longer display durations, fewer participants would have contributed data to any computed average number of pairs recognized. Survival analysis was developed for this kind of scenario; medical studies of survival usually complete with some patients still alive, and often the amount of time a patient participates in a medical study is not fixed.

To run the Cox regression, object pair was entered as a covariate in the first step and display type in the second step. Each object pair for each participant was treated as an independent case. The transparent overlap condition was used as the baseline for the covariate of image type, and simple comparisons were made between survival for it and survival for the other two display types. Of the 2256 cases of an object pair presented to a participant, the pair was recognized 68.5% of the time. Display type contributed significantly to the regression, $X^2(2) = 215.40$, $p < .001$. Contrasts showed that the non-overlap condition had a significantly shorter survival time (objects were recognized after shorter display durations), *Exp(b)* = 1.694, *Wald*(1) = 203.07, $p < .001$, and the opaque overlap condition had a significantly longer survival time (objects were recognized only after greater display durations), *Exp(b)* = 0.660, *Wald*(1) = 121.97, $p < .001$ than the transparent overlap condition.

Recognition of the front and back objects separately. One would expect that in opaque overlap displays, the back object would be harder to recognize than the front object. In the non-overlap condition, there should be no difference between the same two objects. For trials in which at least one object was recognized by the 236 msec presentation, Table 2 presents for each display type the proportion of trials in which the "front" object was recognized first, the proportion of trials in which the "back" object was recognized first, and the proportion of trials in which both were first recognized at the same display duration.[4] For this and all subsequent analyses, the labels "front object" and "back object" were determined from the opaque overlap condition and were used for the same objects in the other two conditions. In all, the front object was recognized first on 59.8% of trials, which can be broken down into 45.9% for non-overlap trials, 72.4% for opaque overlap trials, and 60.1% for transparent overlap trials. Ignoring trials in which both the front and back objects were recognized at the same display duration, Chi square tests demonstrated that the proportion of trials in which the front object was recognized first varied significantly according to display type, $\chi^2(2) = 78.33$, $p < .001$. Follow-up tests found that the proportion of trials in which the front object was recognized first in transparent overlap displays differed significantly from the same proportion in the non-overlap condition, $\chi^2(1) = 20.28$, $p < .001$, and the opaque overlap condition, $\chi^2(1) = 18.60$, $p < .001$.

The time course of recognition of front and back objects for each display type is shown in Figure 4. A stepwise Cox regression survival analysis was run for each display type, each with two covariates entered sequentially: object pair and object position (front/back: whether the object appeared in the front or back in the opaque-overlap condition). For the opaque condition, the individual object in question was eventually recognized in 77.6% of the 1632 cases of an object pair presented to a participant. Adding front/back to the covariates improved the model fit, $\chi^2(1) = 8.17$, $p < .005$. For the transparent condition, the individual object was recognized in 82.0% of 1440 cases of an object pair presented to a participant. Adding front/back to the covariates improved the model fit, $\chi^2(1) = 93.52$, $p < .001$. For the non-overlap condition, the individual object was identified in 89.5% of the 1440 cases. Adding front/back to the covariates improved the model fit, χ^2 (1) = 8.17, $p < .00$. Thus, in all three display conditions, the front object was recognized at shorter display durations than the back object.

(Put Figure 4 approximately here.)

To clarify whether object position affected the three display types equally, two more stepwise Cox survival analyses were run – one for data from only the front object and the other for data from only the back object. For both analyses, the first step included object pair as a covariate and the second step added display type. The front objects were eventually recognized in 88.3% of the 2256 cases of an object pair presented to a participant. Adding display type as a covariate improved the model fit, $X^2(2) = 9.21$, $p < .02$. The front object in the transparent overlap condition was recognized at longer display durations than the front object in the non-overlap condition, *Exp(b)* = 1.064, *Wald*(1) = 4.00, $p < .046$, and at shorter display durations than the front object in the opaque overlap condition, *Exp(b)* = 0.907, *Wald*(1) = 8.632, $p < .004$.

Of the same 2256 cases, 77.3% of the back objects were eventually recognized. Adding display type as a covariate improved the model fit, $X^2(2) = 312.08$, $p < .001$. The back object in the transparent overlap condition was recognized at longer display durations than the back object in the non-overlap condition, *Exp(b)* = 1.783, *Wald*(1) = 265.62, $p < .001$. The back object in the transparent overlap condition was recognized at shorter display durations than the back object in the opaque-overlap condition, *Exp(b)* = 0.595, *Wald*(1) = 210.09, $p < .001$.

Discussion

This experiment tested whether there are differences in how rapidly people can recognize overlapping objects when the displays are transparent versus opaque. The prediction was made that transparency might prove more difficult because transparent displays, being less common, would lead to unexpected and possibly misleading junctions where overlap occurred. However, this prediction was not borne out.

Recognition of non-overlap object pairs was possible at shorter display durations than recognition of overlapping object pairs. The disadvantage for overlap has been seen before (e.g., Watanabe & Cavanagh, 1992). It is most likely due to two factors. First, crowding in displays influences recognition (Pelli, Palomares & Majaj, 2004). Second, when one object overlaps another, only one object can be processed at a time: When one object is seen as figure, the other object is seen as ground and is not processed in the same way (E. Rubin, 2001).

The front object was perceived at shorter durations than the back object in overlapping opaque displays. This is not surprising, as not only is the back object incompletely represented, but due to relative depth cues available from t-junctions, it is likely to be assigned as part of “ground” when segregating figure from ground in the scene (Peterson & Gibson, 1993). Relative depth effects were significant but smaller for transparent displays: Recognition of both front and back objects happened at briefer display durations in transparent overlap displays than in opaque overlap displays. In the transparent condition, then, although the shape of the back objects was fully visible, cues to relative depth biased figure/ground organization toward recognizing the front object first.

Surprisingly, the benefit of the object labeled “the front object” in the opaque overlap displays was also seen in non-overlap displays, in which both objects were seen in complete form and in which neither object had a relative depth advantage. This suggests that the objects assigned to be front and back objects may not have been equivalent in terms of ease of recognition. We are reassured that this does not account for the entire front/back effect because there was a more substantial effect of object position in the overlapping displays than in the non-overlapping displays.

Experiment 2

Experiment 1 did not support the hypothesis that overlapping transparent displays would be processed more slowly than overlapping opaque displays. Although the transparent images in Experiment 1 missed t-junctions, which are important cues to relative depth, they did have other monocular depth cues such asshading. In order to determine whether removing all relative depth cues would result in the hypothesized disadvantage for transparent displays, in Experiment 2 transparent displays were constructed using a method that would remove residual relative-depth information. This change resulted in displays much more like those seen in real X-ray images of luggage than the displays in Experiment 1. As an additional step toward applicability to the luggage-search context, instead of using easily identifiable objects portrayed similarly to natural objects, Experiment 2 used X-ray images of objects similar to those seen in scanned luggage.

Methods

Participants. There were 45 participants in this study (10 male, 35 female), with 15 assigned to each display-type condition. Mean age was 26.3, ranging from 19 to 60.

Apparatus. The experiment was run on a laptop using the Windows XP operating system. Stimulus presentation was again controlled by ePrime 1.2 software.

Stimuli. Stimuli were constructed from X-ray images of individual objects obtained from the US Transportation Security Administration in or around the year 2003. The object set consisted of objects that might be packed in luggage. No object appeared more than once in the set, although for a few object types (e.g., a shoe) two examples were used in the experiment. When selecting objects for the study, we intended that all objects could be identified by participants unfamiliar with X-ray images of objects, although the results will demonstrate that some of the objects were quite difficult to identify. The equipment used to create the X-ray images were scanners built to be used in airports. The scanners colored the objects in the images according to the material making up the object and the thickness of the medium through which the X-ray travelled. The objects appeared orange, green, blue, and black in the resulting images.

Due to limitations in the resolution of the available images of x-rayed objects, the pictures could not be presented as large as they were in Experiment 1 without appearing pixelated. Overlapping displays were approximately 5° x 6° in size. As in Experiment 1, the sizes of individual objects were altered so that each object was similar in maximal extent to all others. A total of 30 pairs of objects were used in the experiment, and each pair had a version in which the objects did not overlap, a version in which the objects were opaque and overlapped, and a version in which the objects were transparent and overlapped. Fourteen pairs were set up as described below. Analyses are based on recognition of those pairs of objects. The remaining sixteen pairs, treated as filler stimuli, were quite similar in appearance, and so should not have changed the nature of the judgments that participants were making.[5]

To create transparent-overlap images, pictures of the two objects were imported into MATLAB. The RGB values were scaled to between 0 and 1, the RGB values of each pixel of the two images were multiplied, and the RGB values of each pixel of the resulting images were scaled back to between 0 and 255. An example of one transparent overlap image from the study can be seen in Figure 5.

---------- Insert Figure 5 about here. ----------

Opaque-overlap images and non-overlapping images were created by layering the images in ADOBE Photoshop. Unlike the stimuli in Experiment 1, the opacity of the layers and the resulting images was not manipulated.

Procedure. The procedure of the experiment was the same as in Experiment 1 except as follows. At the start of the study, participants were told that X-ray images portrayed the material composing objects more than the surface appearance of objects. They were told what the colors represented (Orange - organic materials, Blue/Black - Metal and Green - Inorganic Materials), and were shown three examples. Because it was expected that the nature of the images would make it more difficult to recognize objects, the initial display duration was longer than in Experiment 1 (250 ms) and increased by a larger step than in Experiment 1 (50 ms) in each subsequent cycle. The data collection phase of the study ended after 30 minutes.

Results

Table 1 shows the range of recognition performance by participants and the range of recognizability of objects used in the experiment. Because the data collection phase lasted exactly 30 minutes, different participants reached different display durations by the end of the session. The median final display duration was 650 ms, ranging from 450 to 1200 ms. Figure 6 shows the cumulative number of object pairs recognized at each duration up to 600 msec, averaged across all participants.[6] There is no obvious difference in recognition between the transparent and opaque overlap displays. recognition of overlapping objects required longer display durations than recognition of non-overlapping objects.

(Put Figure 6 approximately here.)

To analyse these data, a stepwise Cox survival analysis was run with non-survival time of an object pair defined as the duration at which a particular participant recognized both objects in the pair. In the first step, object pair was entered as a covariate. In the second step, display type (non-overlapping, opaque overlap, and transparent overlap) was added. Of 630 cases of an object pair being presented to a participant, the pair was eventually recognized in 37.5% of cases. Adding display type improved the model fit, $X^2(2) = 24.31$, $p < .001$. A simple comparison showed that non-overlap displays were recognized at shorter display durations than overlap transparent displays, *Exp(b)* = 1.904, *Wald(1)* = 16.07, $p < .001$. Another simple comparison found no difference between display durations at which transparent and opaque overlap displays were recognized, *Exp(b)* = 0.957, *Wald(1)* = 0.06, $p = .805$.

Recognition of the front and back objects separately. For trials in which at least one object was recognized by the 600 msec presentation, Table 2 presents for each display type the proportion of trials in which the "front" object was recognized first, the proportion of trials in which the "back" object was recognized first, and the proportion of trials in which both objects were first recognized at the same display duration.[7] The labels "front" and "back" were derived from the position of the objects in the opaque display condition, as was done in Experiment 1. Overall, the front object was recognized first on 51.3% of trials, which can be broken down into 43.7% on non-overlap trials, 60.0% on opaque overlap trials, and 52.1% on transparent overlap trials. Ignoring trials in which both objects were recognized at the same display duration, Chi square tests demonstrated that the proportion of trials in which the front object was recognized first varied significantly according to display type, $\chi^2(2) = 6.231$, $p < .05$. Follow-up tests found that the transparent overlap displays did not differ significantly from the non-overlap condition, $\chi^2(1) = 1.48$, $p = .223$, or from the opaque overlap condition, $\chi^2(1) = 1.55$, $p = .214$. Thus, there is evidence that the front object was recognized first more often in opaque overlap displays than in non-overlap displays, but the front object was no more likely to be recognized first in the transparent overlap displays than in the other two display.

The time course of the difference between front and back objects for each display type is shown in Figure 7. A stepwise Cox regression survival analysis was run for each display type, each with two covariates entered sequentially: object pair and object position (front/back: whether the object appeared in the front or back in the opaque-overlap condition). For overlapping transparent displays, of 420 cases of an object pair presented to a participant, 56.4% of individual objects were eventually recognized. Adding object position as a covariate did not significantly improve the fit of the survival model, $\chi^2(1) = 3.026$, $p = .082$. In contrast, the same analysis applied to the opaque-overlap condition found a significant benefit of adding object position as a covariate, $\chi^2(1) = 5.883$, $p = .015$. Overall, of 420 cases of an object pair presented to a participant, 56.7% of individual objects were eventually recognized. The same analysis applied to the non-overlap condition found no benefit of adding object position as a covariate, $\chi^2(1) = 1.40$, $p = .237$. Of the 420 cases of an object pair presented to a participant, 72.9% of individual objects were eventually recognized.

Two more stepwise Cox survival analyses were run – one for data from only the front object and the other for data from only the back object. For both, the first step included object pair as a covariate and the second step added display type. Of 630 cases of an object pair presented to a participant, 61.4% of front objects and 62.5% of back objects were eventually recognized. For front objects, adding display type as a covariate did not significantly improve the model fit, $X^2(2) = 4.609$, $p = .10$. For back objects, adding display type as a covariate did significantly improve the model fit, $X^2(2) = 44.687$, $p < .001$. Recognition occurred at shorter display durations in non-overlap displays than in transparent overlap displays, *Exp(b)* = 1.796, *Wald*(1) = 22.40, $p < .001$. Survival for transparent overlap displays and opaque overlap displays was not significantly different, *Exp(b)* = 0.801, *Wald*(1) = 2.780, $p = .095$.

(Put Figure 7 approximately here.)

Discussion

Experiment 2 tested again whether making displays of overlapping objects transparent would reduce how rapidly people can recognize overlapping objects. In Experiment 2, unlike in Experiment 1, the transparent displays gave no evidence of which object was in front, which is realistic for X-ray images of luggage. As expected, in the transparent overlap condition the display duration required to recognize front objects was not significantly different than the display duration required to recognition back objects, as labeled from their position in opaque overlap displays. In contrast, in the opaque overlap condition there was a significant difference in the required display duration to recognize front and back objects.

The key difference of this experiment compared to Experiment 1 was in the stimuli used. The method of creating transparency removed evidence of which objects were in front. The success of this method is indicated by there being no significant difference between survival of the front and back objects in the transparent overlap displays. In contrast, in the opaque overlap displays, the front objects had shorter survival times (i.e., faster recognition times) than the back objects.

Despite the removal of depth as a cue for segregating objects in the image, transparent overlap displays were processed as easily as opaque overlap displays, as indicated by the display durations at which object pairs could be recognized and the display durations at which individual objects, both back and front, could be recognized.

The displays used in the experiment were based on X-ray scans of individual objects made by a luggage scanning machine. Recognition of the objects was quite low (72.9% recognition of individual objects in non-overlapping displays). One reason for the relatively poor recognition was that participants were given almost no training as to what objects would look like when X-rayed. Trained security personnel would receive training and have far greater experience in looking at X-ray images, and would therefore be likely to recognize objects more easily than our participants. We do not believe, however, that difficulty of recognition influenced the effect of transparency. If it did, there should have been different effects of transparency in Experiment 1, in which recognition was easier, than in Experiment 2. In fact, the effect of transparency was the same.

General Discussion

The research presented here tested whether people would recognize overlapping opaque objects at shorter display durations than they would recognize overlapping transparent objects. Two studies found no increase in the minimum display duration needed for people to recognize overlapping transparent objects compared to the display duration needed for people recognize overlapping opaque objects. In Experiment 1, but not in Experiment 2, the display duration required for recognition actually decreased for transparent objects compared with opaque objects. In both experiments, non-overlapping objects were recognized at briefer display durations than either transparent or opaque overlapping objects.

When relative depth information was available for overlapping objects in Experiment 1, the front object was likely to be recognized before the back object. This is consistent with studies showing that when participants report which of two regions appears to be figure and which appears to be ground, the object whose depth cues indicate it is nearer is usually seen as figure (see, e.g., Peterson & Gibson, 1993). The precedence of front objects was greater in opaque overlap displays than in non-overlap displays in both experiments. The precedence of front objects was greater in transparent overlap displays than in non-overlap displays for Experiment 1, in which transparent displays contained relative depth information, but not for Experiment 2, in which relative depth information was stripped from transparent displays.

We speculate that the elimination of the precedence of front objects in Experiment 2 reflects a relatively greater likelihood of seeing the back object in transparent displays as being in front. It is also plausible that regardless of which was seen in front, the greater information available about the back object in transparent displays contributed, but that would not have explained why the likelihood of recognizing the front object first was lessened in Experiment 2 compared to Experiment 1.

Although the back object was recognized faster in transparent displays than in opaque displays, the pair of objects was not recognized faster in transparent displays than in opaque displays. This suggests that the depth cues may change the order in which the two objects are recognized but not make recognition more efficient overall. This assumes, of course, that recognition of the two objects occurred serially rather than in parallel.

Neither experiment supported the original prediction that objects might be more difficult to recognize in a transparent display than in an opaque display because of a bias in the visual system to expect opacity rather than transparency. Instead, if anything, the evidence supports a slight benefit for transparent displays. It seems that the relative infrequency of transparent objects compared to opaque objects in the visual world does not bias the visual system to assume objects are opaque. Even if the visual system does assume objects are opaque, the richer information in the transparent display about the background object's contours and surface features overcomes this bias. The way the visual system parses information in the region of overlap of transparently overlapping objects may be complex to describe, but is apparently accomplished easily.

It is important to understand that no attempt was made in this study to mimic all features of natural transparency. For instance, in naturally transparent images (but not in X-ray images of luggage) it is common for reflectance off the top layer to partly obscure what is in lower layers, and for reflectance properties of the back layer to change because of the layering. This did not happen in our images; any reflection shown in the original image was in the layered image.Because of this, the way our participants recognized the back object in the current experiments may have been different than if overlapping naturally transparent objects were seen in natural lighting conditions.

Implications for Security Screening at Airports

Experiments 1 and 2 tested whether the threshold display time needed to recognize objects differed for transparent overlap displays versus opaque overlap displays. This is an important shift of laboratory research toward using the kinds of displays used in airport luggage screening, but there are substantial important limitations to how much this research can generalize to luggage screening.

First, although the images of single objects used in Experiment 2 were produced by an industrial luggage scanner, the scanner is no longer being used. More recent scanners may well have differences in image features that are unknown to us. The results are best understood as representing a class of images (X-ray types of images of objects) rather than exactly representing images used currently in security screening. Future studies will have to address whether there are important differences between ways of representing transparency that will affect the ease of recognition.

Second, when security personnel scan luggage, they do not see one or two objects; they see many objects packed into each suitcase. As a bridge between traditional object recognition research and fully applied research, we chose to look at recognition of pairs of objects. The extra clutter from viewing the entire contents of a suitcase will undoubtedly challenge a luggage screener (Pelli, Palomares & Majaj, 2004). In terms of the mechanisms we discuss that could affect recognition, the extra clutter is likely to increase the number of ambiguous extra edges that must be evaluated while parsing objects. Further, the extra cognitive load from making judgments about the entire contents rather than only two objects is not to be ignored (Lavie, Hirst, de Fockert & Viding, 2004).

Third, security screeners have time demands in their task of inspecting luggage which we approximated by imposing an external time limit on how long the pairs of objects were displayed. Although security screeners are under time pressure that limits the time they spend looking at individual objects, they can choose to look longer at displays if they feel such inspection is warranted, which is in contrast to our procedure. Based on what is known about search for targets in displays of multiple objects, it is likely that security screeners would quickly and without awareness dismiss some objects as having low potential for being threats, without fully recognizing those objects. The screeners would then spend more time looking at other objects to recognize them more fully. We speculate that quick dismissal of some objects in suitcases will occur either because the rejected objects are recognized rapidly and easily or because they do not have features known to be associated with threat items.

It may be tempting to believe that luggage screeners are likely to have better performance than our participants because of their experience in processing X-ray images and, in particular, their experience with the threat items seen in X-ray images. Rather than training our naïve participants to recognize threat items, we chose to ask them to recognize objects that would be familiar to them in both experiments. Rather than training our participants about how objects appear when X-rayed, we chose to test performance both when viewing X-ray images (in Experiment 2) and when viewing objects that had a more natural appearance (in Experiment 1).

We attempted to approximate the artificial kind of transparency seen in X-ray images of luggage. We do not have information about exactly how the transparency seen in X-ray images of luggage is produced because that information is proprietary and secure. Along with conveying the shape of all objects, security X-ray images are processed to provide evidence of the materials available in the layered objects. It is clear from inspecting X-ray images of luggage that information about the relative depth of objects is absent from the images. Whereas previous theories of figure/ground segregation suggested that the lack of depth information might strongly impair figure/ground segregation and subsequent object recognition (Nakayama et al, 1989), the results of Experiment 2 suggest that it made little difference.

Although we set out to find evidence of differences in how well people could recognize objects in transparent versus opaque overlapping displays, even more striking is the difficulty of recognizing X-rayed objects in non-overlapping displays as well as in overlapping displays. In Experiment 2, with display durations reaching 600 msec, only 72.9% of objects were recognized in the non-overlapping displays. In contrast, in Experiment 1, in which objects had a more everyday appearance, with display durations of 240 msec 89.5% of non-overlapping objects were recognized. Undoubtedly, giving our inexperienced participants some training on the appearance of X-ray images of objects would have improved recognition accuracy. Even so, the presence of substantial differences between the stimuli used in the two experiments makes it difficult to pinpoint exactly why recognition was more difficult in Experiment 2. Because there are substantial difficulties in recognizing overlapping objects, it is tempting to speculate that finding a way to present X-rayed objects in isolation would improve the accuracy of object recognition based on shape. However, important target items being sought in airports are improvised explosive devices, which may be recognized better through their materials than their shape. The shapes of such devices are undoubtedly extremely variable, and explosive and timing devices may appear as separate objects, connected only by wires.

Implications for Theories of Object Recognition

Theories of object recognition were first developed in relation only to objects appearing in isolation. The fundamental components of such theories (e.g., Biederman, 1989) are the identification of regions bounded by contours, the determination of the shapes of those regions, and the recognition of those shapes. In order to apply such theories to overlapping objects, researchers introduced a parsing process whereby the contours at the region of overlap are determined to be either relevant to an object's shape or irrelevant to it, but perhaps relevant to the other object's shape (e.g., Nakayama, Shimojo & Silverman, 1989). Our initial view of such parsing was that it might be efficient for opaque objects, but inefficient for transparent objects.

In contrast, the results of Experiments 1 and 2 suggest that people's recognition of transparent objects is no less efficient than their recognition of opaque objects. This calls into question the importance of completing regions by parsing contours before recognition begins. As a result, this study adds to an accumulating body of evidence that traditional theories of recognition cannot account for recognition in any but the simplest of displays (see, e.g., Bar, 2004; Navon, 2011; Peterson, 2003; Sanocki, Bowyer, Heath & Sarkar, 1998; Stankiewicz, Hummel & Cooper, 1998). Although we do not propose exactly how object recognition models would need to be changed to account for recognition in transparent displays, it seems that a likely candidate would be a parallel distributed processing model in which local figure/ground information feeds forward into global shape information (see Kim & Feldman, 2009, for further evidence for this approach).

Conclusions

This study was conducted because security personnel commonly examine X-ray images to identify the contents of closed luggage and other containers. Examining X-ray images involves the recognition of transparent objects. Traditional theories of object recognition propose that contour and region parsing is a fundamental part of recognition, but it appeared that such parsing could be inefficient when people process transparent objects. In two experiments, we examined whether people recognize transparent overlapping objects less efficiently than they recognize opaque overlapping objects under conditions in which such that recognition should have been possible. Unexpectedly, we found that people's recognition of transparent objects was no less efficient than their recognition of opaque objects. There are important limitations to whether the results of our experiments will generalize to contexts in which security personnel work. Nonetheless, our results demonstrate that it is possible for the recognition of transparent overlapping objects to proceed as rapidly as the recognition of opaque overlapping objects.

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Footnotes

[1]The results of the study largely upheld this claim. Aggregating across the 18 participants in the opaque display condition, one back object was recognized by no participants, 7 were recognized by 1 to 6 participants, 13 were recognized by 7 to 12 participants, and 27 were recognized by 13 to 18 participants.

The amount and location of overlap used will influence the results of comparing transparent overlap with opaque overlap (see, e.g., Bolfing, Halbherr & Schwaninger, 2008). Taken to the extreme, if two objects were to completely overlap, opaque overlap would render one almost invisible. We wanted to compare recognition in conditions where it was reasonably possible to recognize both objects. Further, because we opted not to create our own objects, but rather use existing databases, we did not have full simultaneous control over the proportion of object overlap and the size of the area of object overlap. It would also matter where the two objects overlapped. It would be a good idea for future studies to vary systematically the amount of overlap and the informativeness of the regions of overlap.

[2]In image processing, two images are combining in a process called compositing. To create the percept of translucency, the color values are combined in a weighted average. In Photoshop, the “opacity” value entered for our images represented the weighting. Making each original image 70% opaque means that each color was computed as 70% its original value + 30% of the background color, which in our case was empty. So this essentially weakened the color values. Then when the images were combined, the overlaid images was 70%*70% of the original pixel colors in the front image + 30%*70% of the original pixel colors in the back image. In general, this can be manipulated further by editing alpha channel values for pixels in the image, but we did not use alpha channels in our image manipulations. Further information about this aspect of image editing can be found in many books about computer graphics (e.g., Brinkman, 2008).

[3]236 msec was the median final duration in the transparent overlap condition; 254 was the median final duration in both the opaque overlap condition and the non-overlap condition. Using 236 as the maximum duration in this figure meant that all data points in the figure had contributions from at least 50% of participants.

[4]When computing whether the front or back objects were recognized first, we included only trials with display durations less than or equal to 236 msec in order to attempt to equate the

amount of data contributed by different participants in the different display conditions. (See footnote 1.)

[5]Filler objects were set up similarly but with mistakes made during stimulus creation. For fourteen pairs, the position of the two objects was not identical in opaque and transparent overlap conditions, and so transparency was not the only thing that changed between the two conditions. For two other pairs, the transparent and opaque conditions were reversed. Note that all inferential-statistic results found for the 14 objects presented here were qualitatively the same for the full set of objects.

[6]600 msec was the median final duration in the transparent overlap condition; 650 was the median final duration in the opaque overlap condition and 700 was the median final duration in the non-overlap condition. Using 600 as the maximum duration in this figure meant that all data points in the figure had contributions from at least 50% of participants.

[7]When computing whether the front or back objects was recognized first, we included only trials with display durations less than or equal to 600 msec in order to attempt to equate the amount of data contributed by different participants in the different display conditions. (See footnote 6.)

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Table 1. Distribution of recognition performance (for participants) and recognizability performance (for object pairs)

What Was Counted	Median	Min	Max
Number of people recognizing both objects in a pair			
For Experiment 1 (48 participants)	36	4	48
For Experiment 2 (45 participants)	16	2	42
Number of object-pairs recognized by a participant			
For Experiment 1 (48 pairs presented)	35	2	47
For Experiment 2 (14 pairs presented)	5	0	12

Table 2. For the three display types, the percent of trials in both experiments in which the front object was recognized first, the back object was recognized first, or both objects were first recognized at the same display duration. Only trials in which at least one object was recognized by the display duration of 236 ms are included.

	Display Type		
Which Object Recognized First	Non-Overlap	Transparent Overlap	Opaque Overlap
EXPERIMENT 1			
Front First	45.9%	60.1%	72.4%
Back First	36.7%	28.7%	19.7%
Both at Same Duration	17.4%	11.2%	7.9%
Number of Trials	712	694	768
EXPERIMENT 2			
Front First	43.7%	52.1%	60.0%
Back First	46.7%	42.4%	36.9%
Both at Same Duration	9.5%	5.5%	3.1%
Number of Trials	199	165	160

Figure 1. a) Opaque square and circle, with t-junctions marked by dashed circles. b) Transparent square and circle, with x-junctions marked.

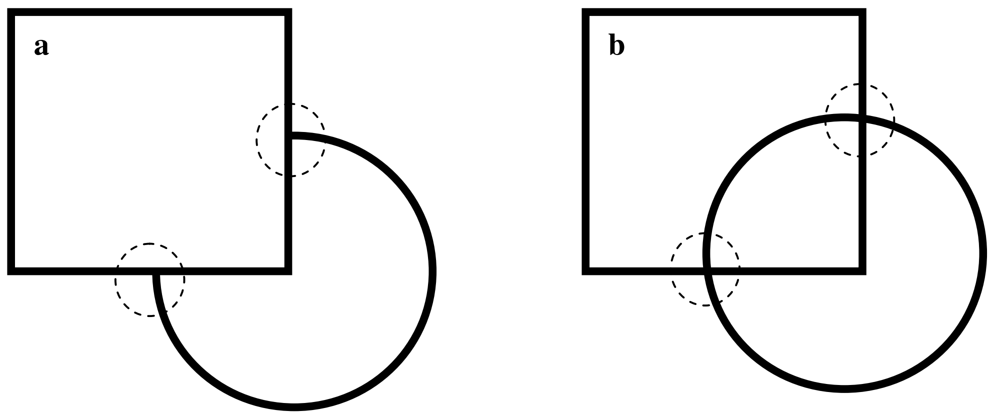

Figure 2. Sample trial from Experiment 1.

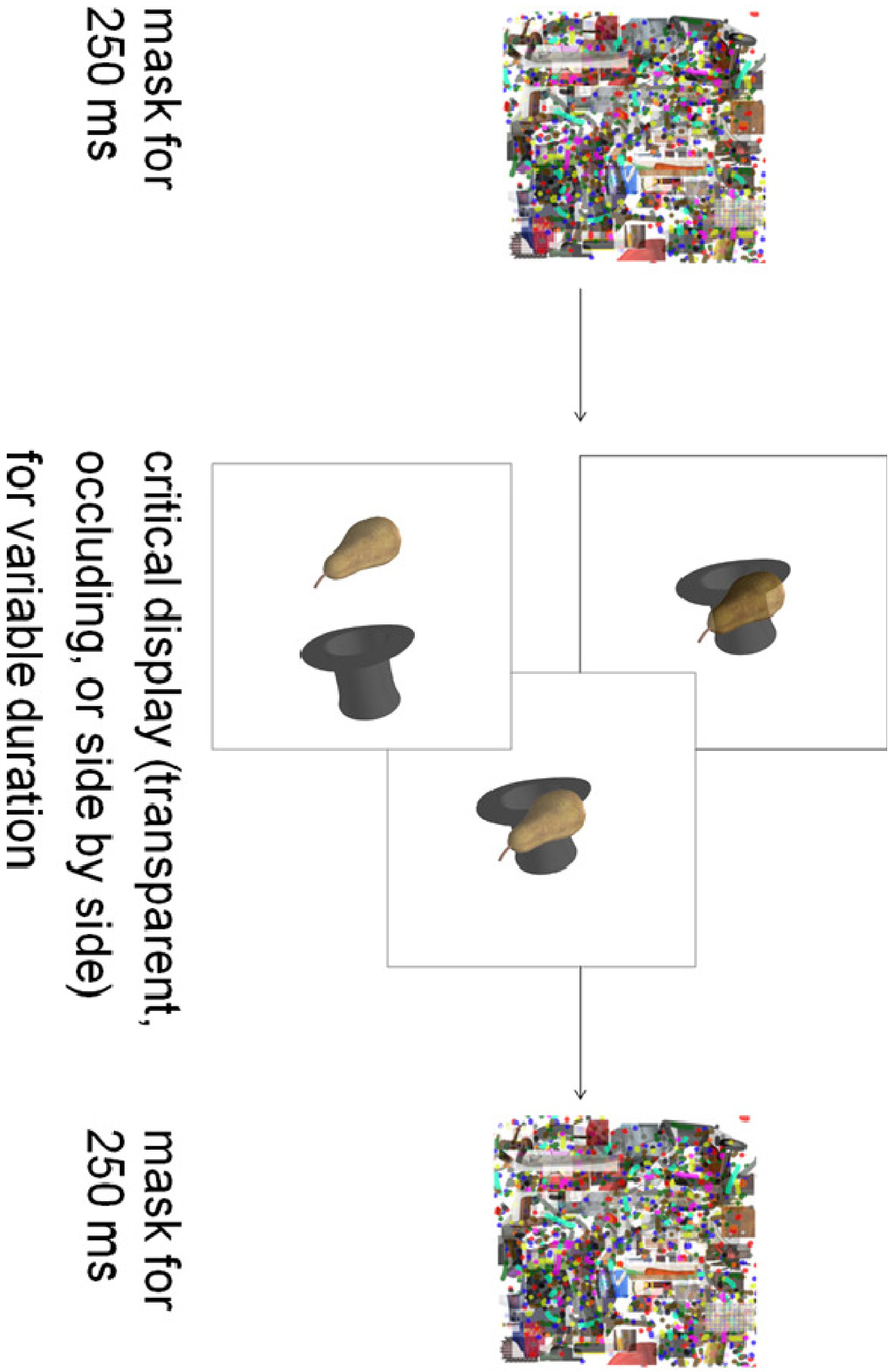

Figure 3. Cumulative recognition of object pairs as display duration increased in Experiment 1.

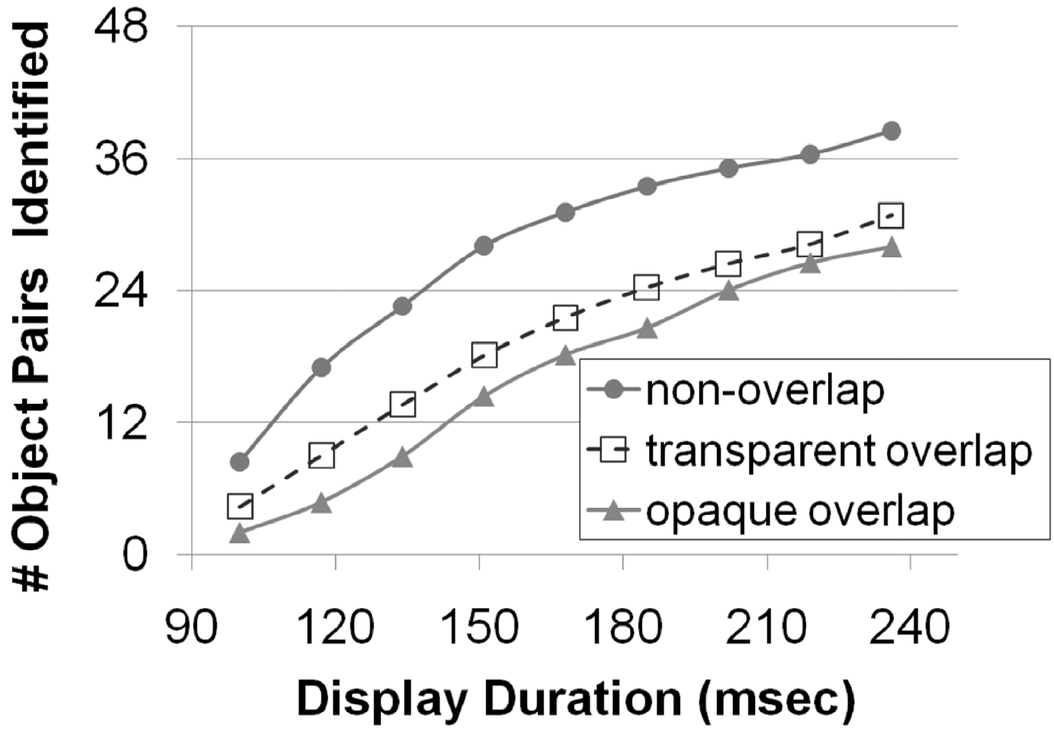

Figure 4. Cumulative recognition of the front and back object as display duration increased in Experiment 1. Which object was labeled front and back was determined from the opaque condition.

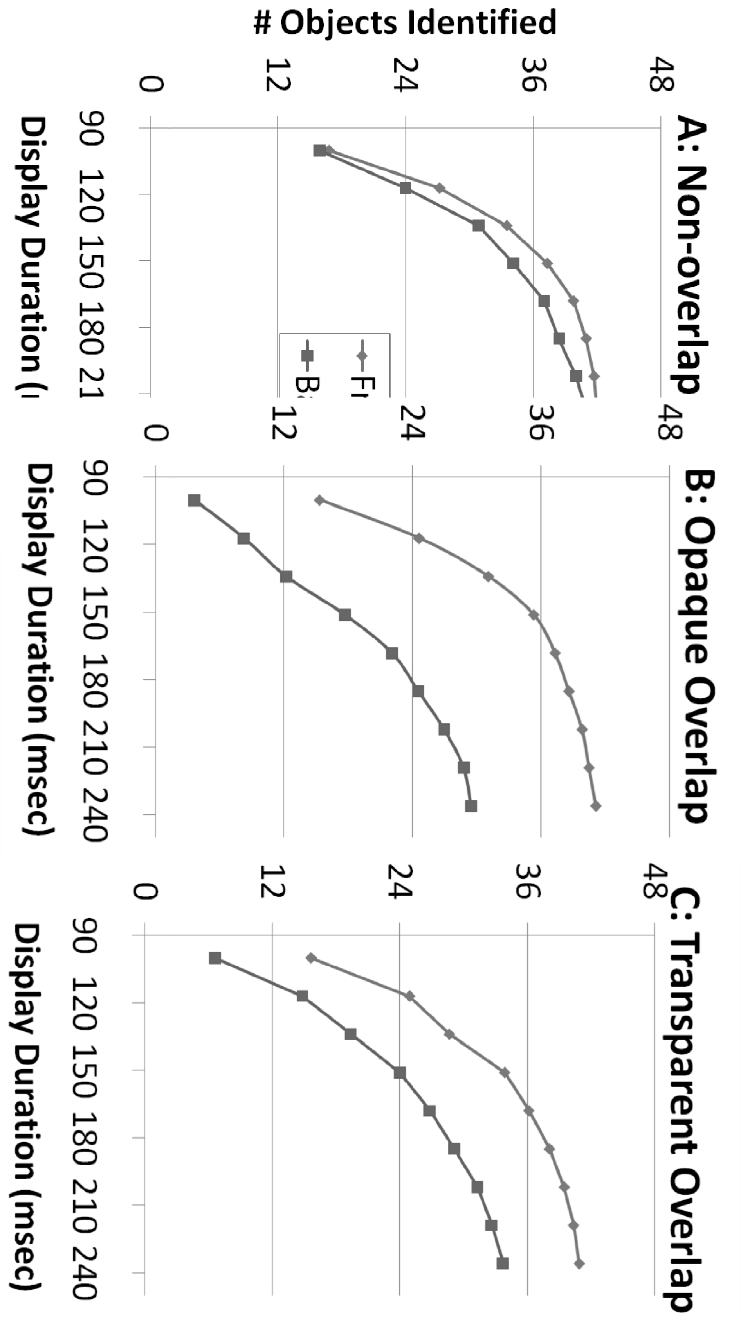

Figure 5. Example of a transparent overlap image from Experiment 2, depicting a shaver in front of a shoe.

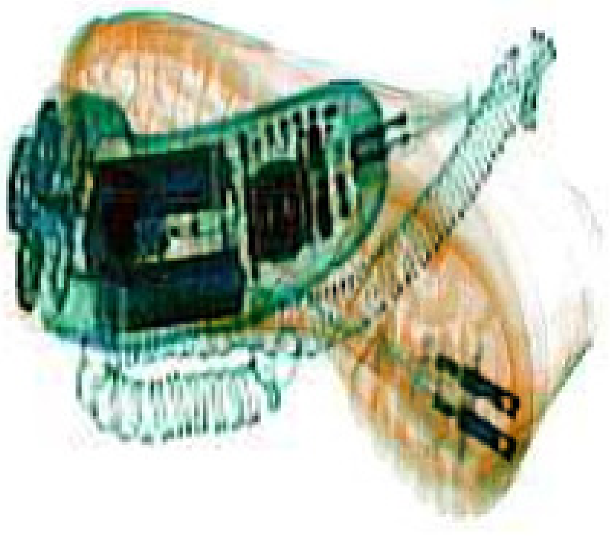

Figure 6. Cumulative recognition of object pairs as display duration increased in Experiment 2.

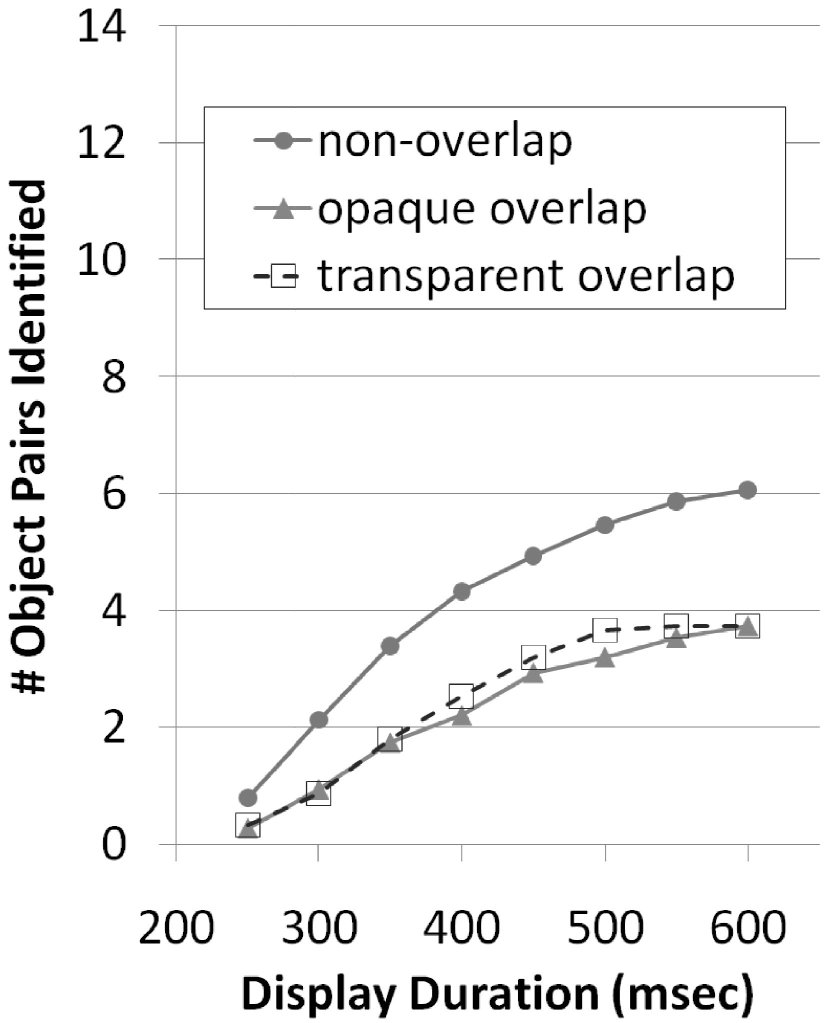

Figure 7. Cumulative recognition of the front and back object as display duration increased in Experiment 2. Which object was labeled front and back was determined from the opaque condition.