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Depth from binocular half-occlusions in stereoscopic images of natural scenes†

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Abstract. Over the past two decades psychophysical experiments have firmly established that binocular half-occlusions are useful sources of information for the human visual system. The existing literature has focused on simplified stimuli that have no additional cues to depth, apart from stereopsis. From this large body of work we can be confident that the visual system is able to exploit binocular half-occlusions to aid depth perception; however, we do not know if this signal has any influence on perception when observers view complex stereoscopic stimuli with multiple sources of depth information. This issue is addressed here with the use of stereoscopic images of natural scenes, some of which have been digitally altered to manipulate a major half-occlusion signal. Our results show that depth-ordering judgments for these relatively complex stimuli are significantly affected by the nature of the half-occlusion signal, but only when highly textured surfaces are viewed. Under such conditions, the replacement of a binocular half-occlusion with background texture slows reaction time relative to performance when the occluded region is consistent with the foreground object. This result is specific to conditions when the depth ordering is correct (ie not reversed) and depends upon the size of the half-occlusion. The influence of the half-occlusion information in the presence of potent depth cues such as perspective, texture gradient, shading, and interposition is convincing evidence that this information plays a significant role in human depth perception.

1 Introduction

When a human observer views an object binocularly, there is a portion of the object, or the background, which is visible to one eye only. This phenomenon is referred to as binocular half-occlusion and is ubiquitous in the natural visual environment (figure 1). While the phenomenon of binocular half-occlusion has been known, at least since the time of Leonardo da Vinci (Richter 1977),[(1)] psychophysical studies of stereopsis prior to the late 1960s did not recognise its potential influence on stereoscopic depth perception. Similarly, most early computational models of stereopsis tended to treat half-occlusion regions as potential sources of noise in the matching process.

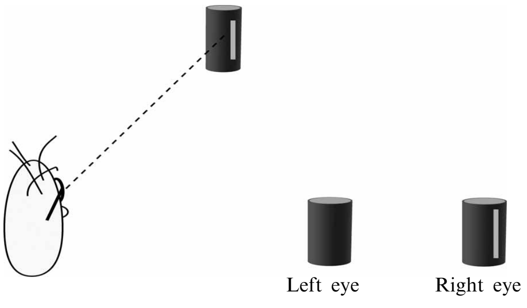

Figure 1. The phenomenon of binocular half-occlusion. The observer views an object (a cylinder here) binocularly. The light strip along the right portion of the object depicts a region visible only to the right eye, as shown in the images depicting the monocular views.

† Earlier version presented at the Vision Sciences Society meeting 2002.

(1) Although Panum's limiting case, a classic example of double-duty matching, may well be related to occlusion (see Ono et al 1992), here we focus on depth from occlusion where double-duty matching is unlikely (Anderson and Nakayama 1994).

It should be noted, though, that pioneers such as Julesz (1960), and Marr and Poggio (1976) did recognise, and comment on, the potential importance of these half-occluded regions.

Lawson and Mount (1967) and Lawson and Gulick (1967) were among the first psychophysicists to investigate empirically the possibility that half-occlusions might provide useful depth-ordering information, and they also demonstrated that occlusion cues in isolation can signal a depth offset. Although it is not clear if he was studying the same phenomenon, Kaye (1978) also showed that relative depth can be perceived in monoptic images (binocularly viewed, monocular stimuli). At approximately the same time, Saye and Frisby (1975) added monocular features to random-dot stereograms (RDSs) to aid vergence. Their aim was to explore the role of vergence in speeding up the perception of depth in RDSs. They found that the monocular features were only effective in reducing reaction times in certain configurations, a result that was difficult to explain from the standpoint of vergence. In retrospect, it appears that the 'successful' configuration was one in which the monocular contour was most consistent with an occluded region. The potential contribution of half-occlusions to depth perception was addressed in Gillam and Borsting's (1988) paper, which showed that the presence of half-occlusions reduced the amount of time required to appreciate depth in simple stereograms containing stereoscopic and binocular half-occlusion depth cues.

As might be expected, if half-occlusions are useful in the natural environment, the advantage provided by the presence of occluded regions depends on the ecological validity of the stimulus geometry (Nakayama and Shimojo 1990). For instance, if the monocular region is visible but located in a region that should be occluded (given the scene geometry), then no advantage is provided. Instead, Nakayama and Shimojo found that such ecologically invalid occlusion relationships result in increased error in judging relative depth (see also Grove and Ono 1999). Consistent with this are reports of binocular rivalry in the presence of invalid occlusion arrangements; such rivalry is not evident in ecologically valid configurations containing monocularly occluded elements (Shimojo and Nakayama 1990). Even in the extreme case where only the occluding surface (a set of periodic bars) is binocular and the intervening regions are dichoptic at all points, a coherent image is seen lying beyond the occluder (Forte et al 2002).

It is clear that binocular half-occlusions are able to promote perception of depth, and there is growing evidence that this depth percept is metric (ie consistent with that perceived via stereopsis). Nakayama and Shimojo (1990) found that participants' perceptions of the magnitude of depth of monocular lines were proportional to the separation of these lines from the binocular edge of the foreground object. This only occurred up to a certain range of separations. However, Gillam et al (1999) reported that the depth perceived in this stimulus arrangement depends critically on the similarity of the form of the half-occlusion. They argued that Nakayama and Shimojo's (1990) stimuli presented an instance of Panum's limiting case, and as such, should not produce metric depth percepts. In a subsequent investigation of this issue Gillam and Nakayama (1999) also reported a dissociation between perceived depth and the width of the unpaired region for these stimuli. In their summary Gillam et al (1999) point out that the conflicting results are likely due to the nature of the stimuli; specifically, if the interpretation of the configuration is well constrained such that a frontal plane solution is available (as in Gillam et al 1999), then metric depth is observed. Recent experiments by Pianta and Gillam (2003a, 2003b) with a geometrically well-constrained stimulus provide strong support for the metric-depth proposal. In related studies, Howard and Duke (2003) suggested that depth from monocular transparency is also able to support metric judgments [though see Grove et al (2006) who argue that disparity cues drive this percept].

The empirical evidence shows compellingly that binocular half-occlusions in a visual display can be useful, and perhaps even significant sources of relative depth information. However, to date, empirical investigations of the impact of such occluded regions on perceived depth have used simplified stereograms, which are deliberately devoid of other depth cues such as perspective, texture gradient, shading, and interposition. It is useful, and arguably even essential, to use simple stimuli to isolate the contribution of a particular source of visual information. However, once it has been demonstrated that a source of information can be used (as has been done for binocular half-occlusions), it is important to put this into context by asking if it is exploited in the presence of other salient cues to depth. The work of van Ee et al (2001) suggests that, when in the presence of valid stereoscopic signals, half-occlusions do not influence stereoscopic thresholds. But, again, their stimuli contained no other congruent depth cues—information that would be present in natural scenes. Thus the goal of the research reported here is to determine if the human visual system uses binocular half-occlusions to make depth judgments in stereoscopic images that also contain veridical depth cues, such as linear perspective, texture gradient, shading, and interposition.

2 General methods

2.1 *Subjects*

All observers in the following experiments had either normal or corrected-to-normal vision and good stereopsis (assessed with the Randot™ stereotest). Ten observers participated in experiment 1 and twelve in experiment 2. Some, but not all, observers participated in both studies. All subjects were volunteers recruited from neighbouring laboratories or through word of mouth; none received payment.

2.2 *Apparatus*

Stereoscopic images (1024×768 pixels) of the stimuli were taken with two Olympus Camedia C-2500L™ digital cameras mounted on optical rails at a separation of 7.0 cm. The cameras were calibrated and the images rectified with the Camera Calibration Toolbox for Matlab™ (www.vision.caltech.edu/bouguetj/calib_doc/index.html). Stimuli were presented with an Electrohome Model Marquee-8000 CRT projector and a 2.35 m by 1.73 m back-projection screen. All testing was performed in a dimly lit room. The observers were seated in a chair 1 m from the screen with their heads positioned in a chin-rest. They wore Stereographics™ 3-D shutter glasses that switched in synchrony with the projector (at 120 Hz, giving 60 Hz per eye). This allowed presentation of the appropriate stereoscopic half-images to each eye separately. A Macintosh G3 computer and MATLAB™ software were used to present the stimuli, and to record the observers' responses.

2.3 *Stimuli*

Two sets of stimuli were created, one in which the half-occlusion along one side of the stimulus was present, and the same image with the occluded region modified with Adobe Photoshop™ image-editing software. When manipulating the images, the monocular regions of interest were carefully removed with cropping tools, and 'filled in' with a sample of the appropriate background area. A magnified version of this alteration is shown in figure 2, which depicts one of the textured stimuli from experiment 2 (the filling-in process was more complicated for this study in which multiple textured surfaces were used). As described below, the primary difference between the stimuli used in experiments 1 and 2 was the nature of the texture used on the stimuli and in the background regions.

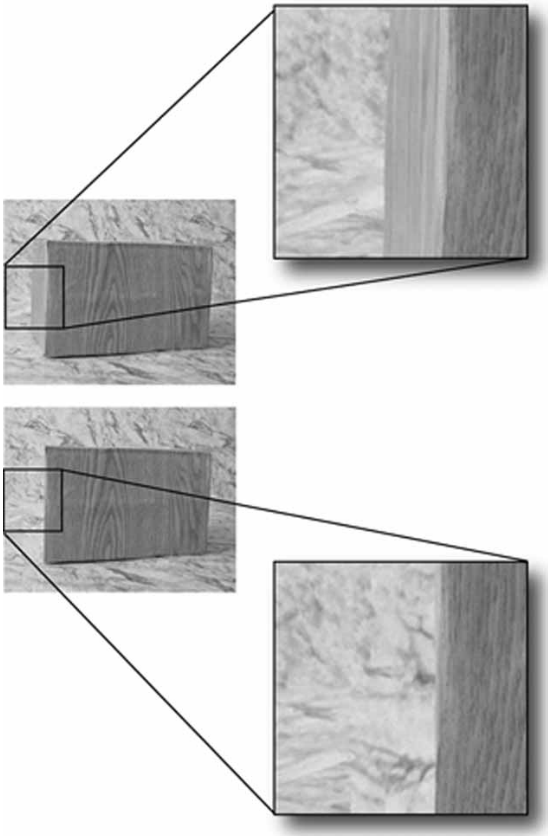

Figure 2. Magnified portions of the half-occlusion in the original image (upper inset), and with the half-occlusion replaced with background texture (lower inset). Note that these left-eye images are otherwise identical, and can be viewed as a stereogram in figure 4 below. (Figures 2–4 are shown in colour on the *Perception* website at http://www.perceptionweb.com/misc/p5708/.)

2.4 *Experiment 1*

Six rectangular cardboard boxes with minimal texture were photographed from a distance of 1.0 m. The boxes ranged in size from 15 cm × 5 cm × 8 cm to 26 cm × 22.2 cm × 16.2 cm. Each box was positioned so that a corner was toward the observer and, at that edge, a portion of the box was occluded from the right eye (see figure 3). The distance from the stimulus to the camera was measured from the leading corner. Depending on the box used, the width of the occluded region varied from 2.3 to 6.9 deg. The foreground and background were covered with a black curtain, and the boxes were positioned on a pedestal.

2.5 *Experiment 2*

Three identical boxes (26 cm × 22.2 cm × 16.2 cm) served as stimuli, and each was covered with one of three non-repetitive textures (granite, marble, wood grain). As in experiment 1, the boxes were oriented with a corner towards the observer, such that a region of the box was not visible to the right eye. All combinations of the three textures were used on the object, background, and foreground surfaces (see figure 4 for one example with wood grain on the object and marble in the foreground and background). The stimuli were carefully situated to create half-occlusions with widths of 1.8, 2.2, and 4.4 deg. For this set of images, we deliberately included a foreground texture that was visible in all images. This extended region provided strong texture gradient cues and cast shadows, neither of which was apparent in experiment 1. Owing to the scene layout and lighting, the shadows never lie near the half-occlusion, but fall from the opposite side of the box (figure 4).

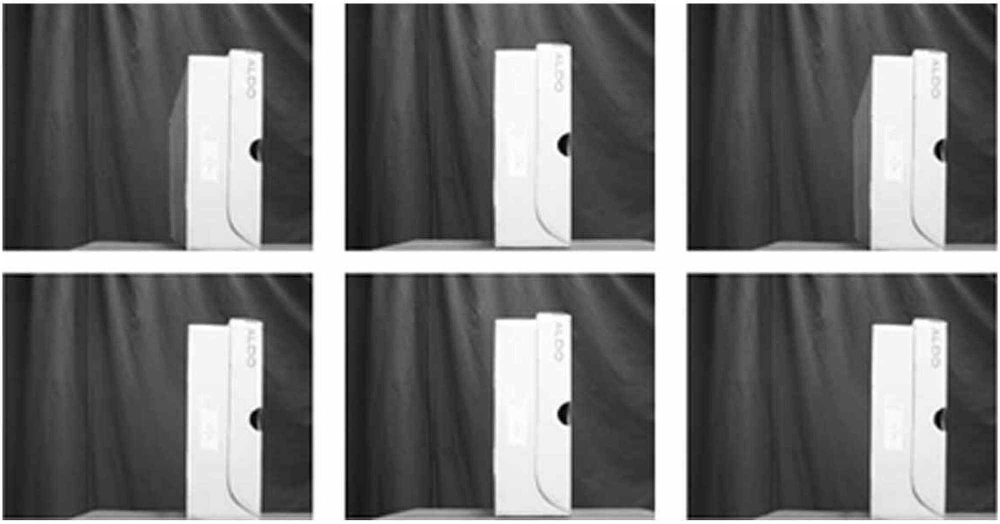

Figure 3. Sample images used in experiment 1, with the foreground occlusion region present (top row) and absent (bottom row). For crossed fusion, correct depth ordering will result from fusing the right and middle columns, and reversed depth from fusing the left and middle columns. For uncrossed fusion, the left and middle images will produce correct depth ordering, while the right and middle images will produce reversed depth.

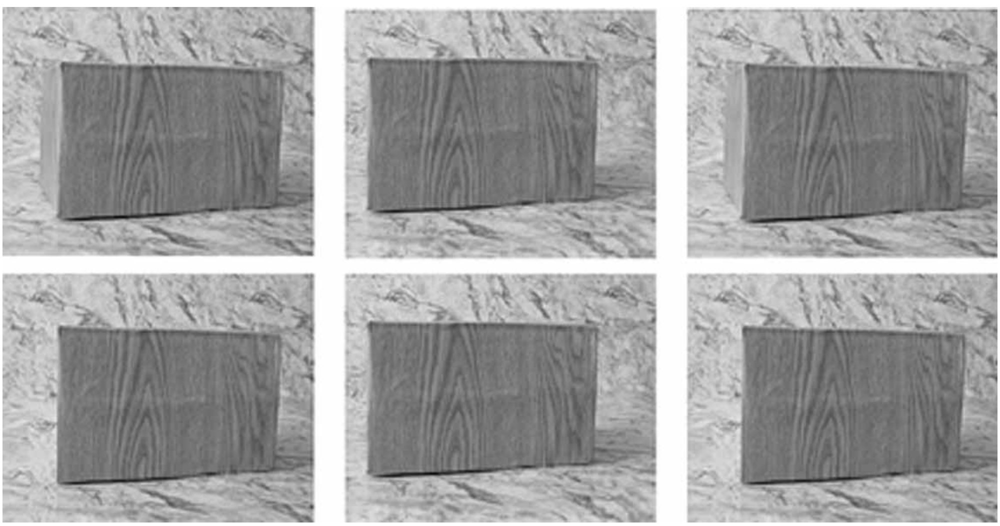

Figure 4. Sample images used in experiment 2, with the foreground occlusion region present (top row) and absent (bottom row). In this example the object has the wood-grain texture while the background and foreground have marble texture. For crossed fusion, correct depth ordering will result from fusing the right and middle columns, and reversed depth from fusing the left and middle columns. For uncrossed fusion, the left and middle images will produce correct depth ordering, while the right and middle images will produce reversed depth. Magnification of the altered half-occlusion can be seen in figure 2.

2.6 *Procedure*

In both experiments the images were presented in random order, three times apiece, and presented correctly to the left and right eyes (depth correct) or exchanged (depth reversed). The observers' task was to indicate as quickly and as accurately as possible, with the use of a keyboard, whether the depth ordering was correct or reversed.

This particular task was chosen because the most useful (and likely) signal that binocular half-occlusions can provide the visual system is that of depth ordering at depth discontinuities. Further, unlike many depth judgments, this task is surprisingly difficult for most observers, so ceiling/floor effects are uncommon. Because of the inherent difficulty in detecting full-field depth reversals (in natural scenes) we tested the observers prior to the main experiment and allowed them to practice the task until they performed with at least 67% accuracy. All observers reached this criterion level of performance except for two individuals, who were not subsequently included in the main experiment. During testing we measured both reaction time, and the veracity of the response. The average reaction time for each condition was then calculated for correct trials only in order to reduce variance due to anticipation.

3 Results

3.1 *Experiment 1*

The results of experiment 1, averaged across ten subjects and all test stimuli, are presented in figure 5. Trials in which the depth ordering was correct or reversed are shown on the left and right, respectively. As expected, reaction times were elevated when the depth ordering was reversed; however, there was no effect of the nature of the half-occlusion region. On average, accuracy was near 67% but varied across subjects; a posteriori analyses revealed no consistent pattern in the accuracy data.

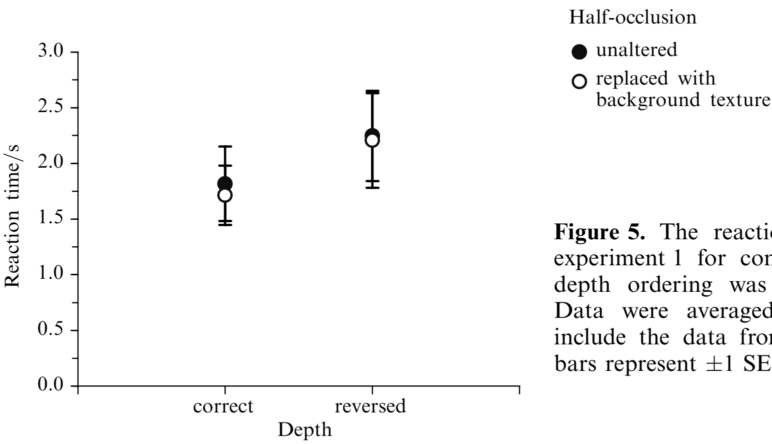

Figure 5. The reaction time results from experiment 1 for conditions in which the depth ordering was correct or reversed. Data were averaged across stimuli and include the data from ten subjects. Error bars represent ±1 SEM.

Closer examination of the influence of the width of the occluded region also showed no significant differences. While this null result appears to downplay the potential role of half-occlusions in depth judgments in naturalistic images, the salience of the half-occlusion signal may have been degraded by the reduction in surface texture in the foreground object. That is, in this preliminary experiment we used untextured boxes to minimise the effect of texture gradients on performance. It is possible that the limited amount of surface texture disadvantaged depth ordering from half-occlusions by making it difficult to identify unmatchable regions in the scene. Further, by limiting the texture- and shadow-based information, we may have inadvertently made it easier for the visual system to misinterpret the stimuli. That is, the images with the modified occlusion regions could be interpreted as flat, oddly shaped, cardboard cut-outs seen from an 'accidental' vantage point. Because these stimuli would not necessarily create a half-occlusion, the absence of that region should not influence performance. In experiment 2 we repeat this study, but use boxes covered with rich texture simulating wood grain, marble, and granite. To enhance the amount of texture and shading information we placed the boxes on an extended foreground plane that was visible in the test images.

3.2 *Experiment 2*

In our first experiment the boxes, and the background and foreground regions contained little surface texture. In this study we used the texture patterns described in section 2 to provide a more salient interocular matching signal and to enhance the percept of 3-D form. We also ensured that the foreground plane was visible in the images. Because our textures varied considerably in their overall luminance and colour, we tested all three samples (wood grain, granite, and marble) in all combinations of the foreground object, background, and foreground surface. For instance, figure 4 depicts the stimulus created with wood grain on the object and marble in the foreground and background. By ensuring that all combinations of texture and location were tested, we eliminated the possibility that interocular contrast ordering alone could have driven the observers' responses (Anderson and Nakayama 1994). The observers' task was identical to that described in experiment 1 and we recorded their reaction times and accuracy. The depth-ordering results obtained with textured stimuli are shown in figure 6 for twelve observers.

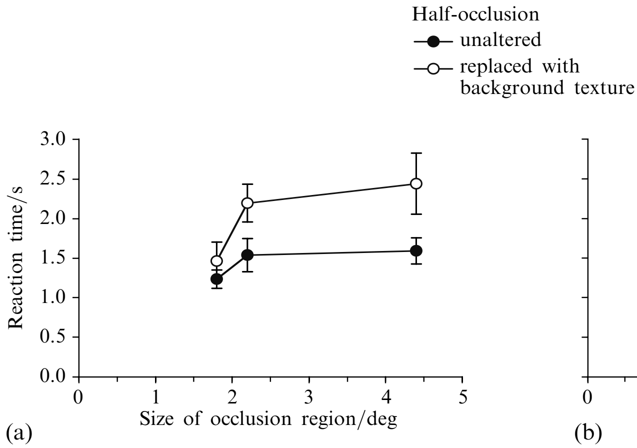

Figure 6. Reaction times as a function of the width of the occlusion region for conditions in which depth ordering was correct (a) and reversed (b). Data were averaged across twelve observers, and the error bars represent ± 1 SEM.

From figure 6a it is evident that the replacement of the half-occlusion along the target stimulus with background texture increases reaction times, but only when the depth ordering is correct. Paired t-tests confirm that in the depth-correct conditions there is no effect of the status of the occlusion region when it is only 1.8 deg wide ($p = 0.18$). Removal of the occluded region, however, results in higher reaction times for both the intermediate ($p = 0.02$) and largest ($p = 0.04$) regions. This slowing of response time at widths of 2.2 and 4.4 deg by a factor of 1.5 is also statistically significant ($p = 0.007$). Figure 6b shows that these effects are not seen when the depth ordering is reversed. Instead, reaction times remain constant (and relatively high) regardless of the size or state of the half-occluded region, an observation confirmed by paired t-tests with p values equal to or greater than 0.1 in all cases.

A potential concern about our paradigm is that the increase in reaction time in experiment 2 was not caused by the manipulation of the half-occlusion region, but that the image manipulation caused artifacts that in some way disrupted the observers' ability to use the stereoscopic signal. However, if this were true, then the increase in reaction times should have occurred on both the depth-correct and the depth-reversed trials, for the identical images were viewed in the two cases. The fact that the decrement in performance occurred only when the depth ordering was correct makes it very unlikely that this pattern of results is due to the image manipulation itself. In addition, if this result were due to an artifact caused by the image manipulation, we might expect a corresponding reduction in accuracy on trials in which the altered image was viewed. Instead, accuracy remained near 67% for all conditions.

4 Discussion

There is no apparent effect of manipulating the occluded region in our first study where texture-based information is minimal. However, in experiment 2 we find significant impact of manipulation of the half-occlusion when the texture defining the object, background, and foreground is increased. This difference cannot be attributed to the range of sizes of the occlusion regions used, for there is considerable overlap across the two conditions (2.3 – 6.9 versus 1.8 – 4.4). Further, in experiment 2, we find that there is an effect of the width of the half-occlusion region. At a width of 1.8 deg there is no difference between the occlusion conditions, but at widths between 2.2 and 4.4 deg reaction times are significantly longer when the texture in the half-occlusion is altered to match that of the background. There is a slight increase in reaction time between 2.2 and 4.4 deg, and this, combined with increased response variability, suggests that the half-occlusion signal is not binary, but varies with the extent of the region. This observation is consistent with the recent experiments of Pianta and Gillam (2003b), in which perceived depth from occlusion varied linearly with the width of the region.(2) Significantly, in the depth-correct condition (figure 6a) exactly the same depth information was present from stereopsis, texture gradient, perspective, shading, and interposition; nevertheless, alteration of a half-occluded region was still able to disrupt performance. Thus, our experiments extend the work of Gillam and Borsting (1988), whose stimuli consisted of stereoscopic and half-occlusion information, but did not contain additional consistent depth cues, and whose stimuli were computer-generated bar-and-line patterns. Here we show that the visual system is sensitive to binocular half-occlusion information in the presence of multiple compelling depth cues with natural imagery.

4.1 *The role of surface texture and shadows*

We argue that the critical difference between experiments 1 and 2 is the relative amount of surface texture and the presence of cast shadows, but it is not immediately obvious how or why these cues and the half-occlusion signals interact to slow response time.

Texture may contribute to our depth-ordering judgments in at least two ways. The most obvious of these is in providing a salient texture gradient on the ground plane, which can disambiguate its slant in depth. Second, because the three textures used here are not periodic, they should aid binocular correspondence throughout the scene, and on the surfaces of the box. Another way in which the stimuli in the two experiments differ is the presence of cast shadows. The images used in experiment 1 were taken with the boxes on a covered pedestal with no visible cast shadows. In experiment 2 the images were taken so that the ground plane is visible, and as a result, so too are cast shadows.

It is possible that the surface texture and the cast shadows provide a stronger sense of solid, 3-D shape in experiment 2. The relative lack of this information in experiment 1 may make it easier for the visual system to interpret the stimulus as an irregular planar figure seen from an 'accidental' vantage point. Following this logic, it is the strong sense of 3-D form in experiment 2, resulting from the texture and shadows, that makes it difficult to disregard the altered half-occlusion signal. The resultant conflict slows reaction times.

(2) In experiment 2 the height of the stimuli remained constant across all conditions so the half-occlusion signal strength is determined solely by the width of the region.

As noted previously, this interference only occurs when the depth order is correct; when the depth ordering (stereopsis signal) is reversed, reaction times for the original and altered images are equivalent and slow. It is notable that, in the reversed condition, reaction times are consistently as high as reaction times in the depth-correct condition at the largest occlusion width—regardless of the status of the half-occlusion. One interpretation of this is that performance is so degraded in the depth-reversed trials, that it swamps any effect of the half-occlusion manipulation. If this were true, then we might expect to find increased variability in the depth-reversed conditions; but this is not the case. Another possibility is that the cue conflict created by reversing the stereoscopic information has an effect similar to that observed in experiment 1. That is, without veridical stereoscopic information regarding the 3-D form of the object, the visual system is more likely to accept the 'planar object' interpretation described previously. In this case, one would not expect performance to be influenced by the status of the half-occlusion region in the stereo-reversed conditions.

4.2 *A possible role for half-occlusions*

It is established that the presence of half-occlusions can speed up depth processing in simple displays (Gillam and Borsting 1988) and, as we show here, in more naturalistic stimuli with additional depth cues. However, at this point it is unclear whether the half-occlusion signal should be considered a distinct cue to depth, or whether it is somehow integrated within the stereoscopic system. Our preliminary results (Wilcox et al 2005) and those of van Ee et al (2001) suggest that there is little facilitatory interaction between binocular half-occlusions and stereoscopic-depth signals. An explanation for the role of half-occlusions in depth perception that incorporates much of the varied literature on this topic is that the half-occlusions play an important role in the rapid identification and labeling of 3-D discontinuities in the environment (see Gillam and Borsting 1988, and Anderson and Nakayama 1994). Simply put, the half-occlusions may be used to rapidly determine the locations in a scene with depth discontinuities and, because the signal is signed, may also give a coarse estimate of the depth ordering that can then be refined by the stereoscopic system. Experiment 1 shows that it is possible for the visual system to ignore the removal of half-occlusion regions, but this occurs under conditions where an alternative interpretation of the stimulus is possible (ie an irregular figure viewed from an accidental vantage point). When the 3-D form is made less ambiguous by adding surface texture and shadows, the binocular half-occlusion information must be consistent with the additional depth cues, or the interpretation of depth ordering is delayed. This is surprising, for it means that, even though multiple additional cues could in theory be exploited to rapidly complete this task, in practice they are not.

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