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Modulating motion-induced blindness with depth ordering and surface completion

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Abstract

Motion-induced blindness is a striking phenomenon in which salient static visual stimuli "disappear" for seconds at a time in the presence of specific moving patterns. Here we investigate whether the phenomenon is due to surface completion of the moving patterns. Stereo-depth information was added to the motion stimulus to create depth ordering between the static and moving components of the display. Depth ordering consistent with the perceptual occlusion of the static elements increased motion-induced blindness whereas placing the moving components behind the static elements decreased the static dot disappearance. In a second experiment we used an induced surface stimulus configuration to drive the motion-induced blindness phenomenon as further evidence of the importance of surface completion and interactions during visual processing.

Keywords: Surface completion; Motion

1. Introduction

Motion-induced blindness is a remarkable example of the "disappearance" of salient visual objects from perception (Bonneh, Cooperman, & Sagi, 2001). In this phenomenon, high-contrast stationary elements are superimposed on a rigidly moving pattern. Observers report sporadic disappearance of the stationary stimuli. In their study, Bonneh et al. (2001) used a stimulus (2D configuration, depicted in Fig. 1(a)) consisting of blue cross elements arranged in a grid rotating around its center point at a constant velocity. Three static yellow dots were superimposed in the center of the moving stimulus, in an inverted triangle formation. During prolonged viewing of this configuration the static dots "disappeared" from perception for seconds at a time. Bonneh et al. (2001) demonstrated that the phenomenon is robust and does not reflect retinal suppression, sensory masking or adaptation. Motion-induced blindness thus joins other visual phenomenon such as binocular rivalry and stabilized retinal images as cases where visual stimuli that are physically present do not register consciously.

The explanation given by Bonneh et al. (2001) for motion-induced blindness is based primarily on the influence of attentional mechanisms. They postulated that when viewing a motion-induced blindness stimulus the visual system operates in a winner-takes-all strategy. In this situation, the system slows down the rate at which attention can be shifted and competing objects are seen one at a time. Thus the rivalry and suppression of moving and static objects could be modulated by attention or between attention mechanisms assigned to the different objects in space. In the present study, we investigate whether motion-induced blindness results from surface interactions between the moving and static elements of the stimulus. Perhaps what underlies motion-induced blindness is the completion of the grid elements into a perceptual surface, which interacts with the static dots. If this is the case, motion-induced blindness may modulate according to simple occlusion principles, with more dot disappearance observed when the moving grid is presented stereoscopically in front of the static dots, and less disappearance when the grid is presented behind the static dots. Of course, the static elements are never *physically* occluded by the moving elements. To investigate the effect of depth ordering, we reconstructed the stimuli used in the original study except that our stimulus presentation was dichoptic, using a mirror

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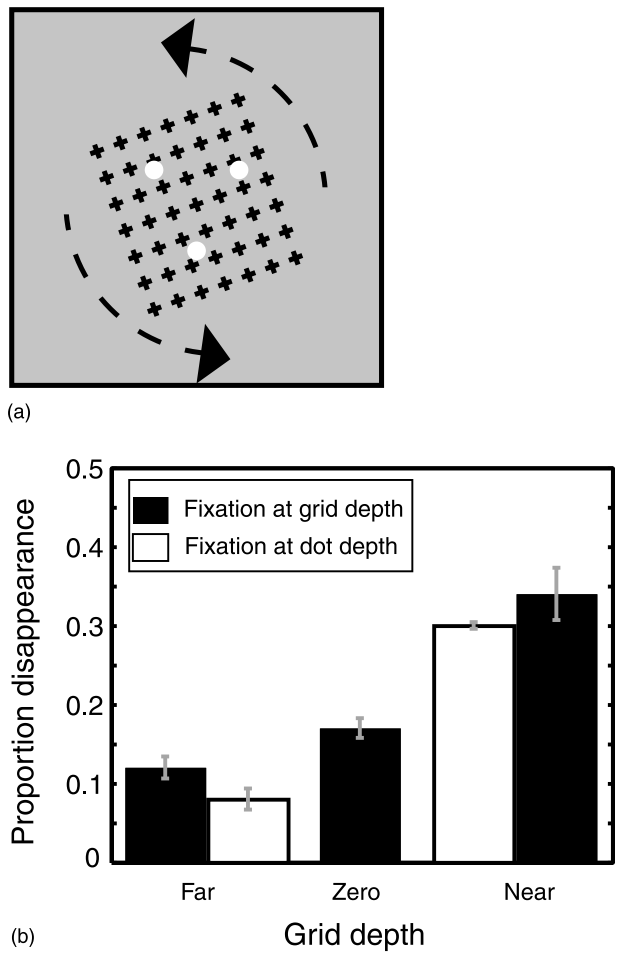

Fig. 1. Results of Experiment 1: (a) schematic representation of the stimulus used in Experiment 1 (see Section 2 for details), (b) dot disappearance as a function of depth ordering of the moving grid and static dots. Black bars indicate conditions where the observer fixated at the depth of the grid and white bars indicate conditions where fixation was at the depth of the static dots. Error bars indicate ±1 standard error.

stereoscope. We presented the grid stimulus in front of, in the same plane as, or behind the static dots. In a second experiment, we used an induced surface made of Kanizsa "pac-men" elements (Fig. 2(a) and (b)) to further test whether surface completion of the moving elements can explain motion-induced blindness.

2. Methods

2.1. Apparatus

Computer-generated stimuli were presented stereoscopically via a split-screen Wheatstone configuration at a viewing distance of 114 cm. A chin rest and forehead rest supported the observer's head during the experiment.

2.2. Stimuli

In Experiment 1, a $6^\circ \times 6^\circ$ field composed of 49 equally spaced blue cross elements was rotated about its center-point at 30°/s. Superimposed on the grid were three static yellow dots, equally spaced on an imaginary circle with radius 1.75°. In Experiment 2, the blue Kanizsa elements (depicted in Fig. 2(a)) were centered on the corners of an imaginary $6^\circ \times 6^\circ$ square. The elements were 2° in diameter. Three depth conditions were used; where the moving stimulus was presented stereoscopically: (a) 2 cm in front of the static dots, (b) at the same depth as the dots, or (c) 2 cm behind the dots. It is important to note that the monocular information was identical in the two non-zero depth conditions, the only difference being that the stimuli were presented to opposite eyes. In Experiment 1, the fixation cross was placed in the depth plane of either the dots or the grid. In Experiment 2, the fixation cross was always at the depth of the dots.

2.3. Procedure

Five observers participated, including the three authors. An experimental session consisted of two trials for each condition (five conditions for Experiment 1, six for Experiment 2). The trials were randomized within a session. Observers participated in five sessions for each of the two experiments. During each 30-s trial, observers viewed a fixation cross in the center of the display and indicated dot disappearance by pressing and holding any combination of three keys (one per dot) and releasing the key when the dot(s) reappeared. For each observer and condition, the duration of all key presses were added together to give a single value. For each observer, dot disappearance in each condition was expressed as a proportion of the sum of the total dot disappearance across all conditions. These values were then averaged across observers.

3. Results

3.1. Averaged amount of dot disappearance

The results from Experiment 1 are depicted in Fig. 1(b). Shown are the normalized results of all observers, with each condition expressed as a proportion of total dot disappearance across all conditions (see Section 2). Normalizing the data in this manner allowed us to compare data across observers, as individuals varied in the overall magnitude of reported disappearance; e.g. 4.2–26.7 s in condition (a), see below for more details. However, all observers showed the same depth ordering effect: When the grid was presented in front of the yellow dots, the amount of disappearance was greater than

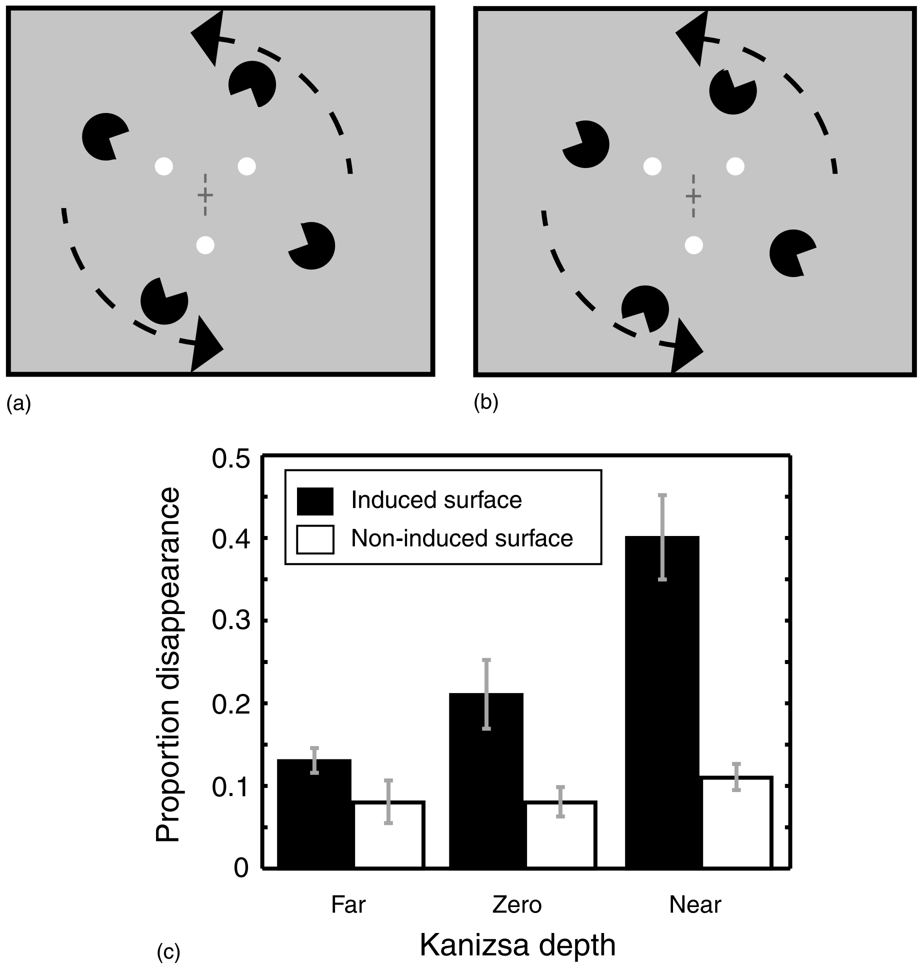

Fig. 2. Results of Experiment 2: (a) and (b) schematic representation of the stimuli used in Experiment 2 (see Section 2 for details), (c) dot disappearance as a function of depth ordering of the moving and static stimuli. Black bars indicate conditions where the stimulus was as depicted in (a), white bars indicate conditions where the orientation of the Kanizsa elements was that depicted in (b). Error bars indicate ±1 standard error.

when the two were presented on the same depth plane, which was greater than when the grid was presented behind the yellow dots. A one-way analysis of variance (ANOVA) showed a significant effect across conditions ($F_{(4,24)} = 38.88$, $p < 0.00001$). Post-hoc analysis revealed that manipulating the plane of fixation had no statistically significant effect (black vs. white bars).

The results of Experiment 1 show a clear effect of depth ordering on motion-induced blindness. Dot disappearance was modulated according to simple occlusion principles. Our data are consistent with the idea that surface completion of the moving elements contributed to the phenomenon. However, it may be the case that local stimulus interactions also contributed to the observed result, as evidenced by the presence of a small amount of dot disappearance in the far condition. For example, the path of the moving grid elements may have been extrapolated, masking the static elements that fell on the predicted trajectory (Bonneh et al., 2001). To address this point, we repeated the experiment using an illusory surface, induced by four Kanizsa "pac-man" elements, instead of the grid pattern. The elements were oriented either to form an induced square surface (Fig. 2(a)), or were each rotated 180° (Fig. 2(b)) so that no perception of an induced surface resulted. Note that the local motion information is equivalent in these two conditions. The fixation cross and nonius lines were always in the same depth plane as the static yellow dots. The regular and rotated Kanizsa stimuli were presented at the same three depths used in the previous experiment. Mean proportion data, calculated in the same way as in Experiment 1, is given in Fig. 2(c). When the Kanizsa elements were oriented to produce a clear induced surface the data are similar to those in the grid experiment (black bars). However, when the same Kanizsa elements were rotated 180° in order to eliminate the induced surface, very little dot disappearance was produced (white bars). An ANOVA showed a significant effect across depth conditions ($F_{(2,24)} = 12.98$, $p < 0.0001$), surface type ($F_{(1,24)} = 39.08$, $p < 0.0001$), and their interaction ($F_{(2,24)} = 7.25$, $p < 0.003$). The mean disappearance time in this experiment was on average

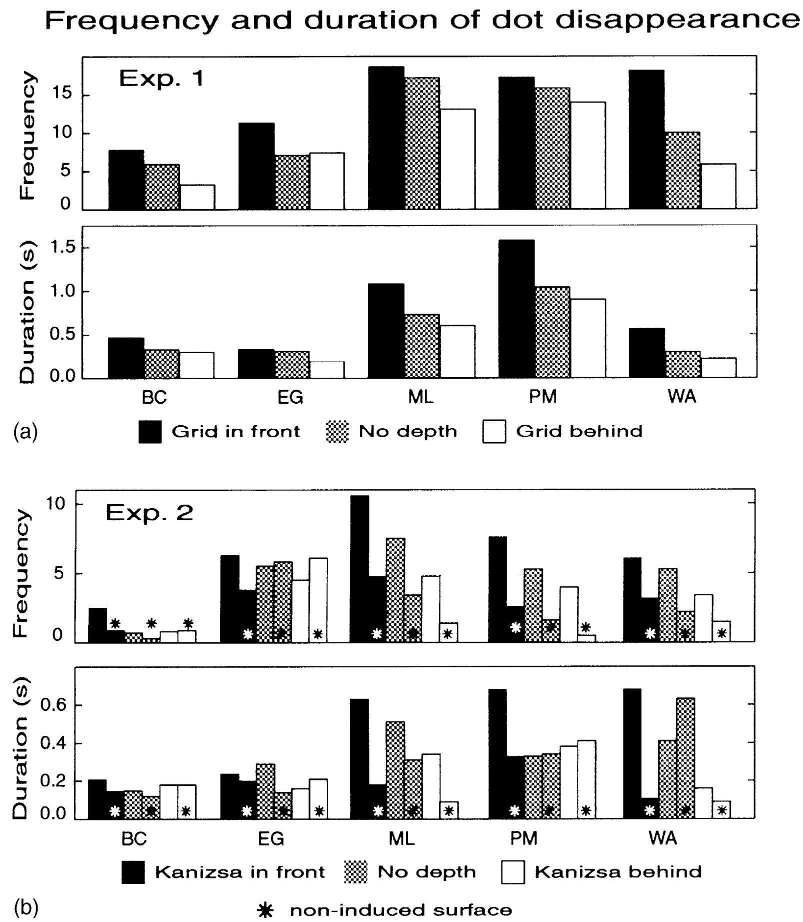

Fig. 3. Individual subjects' dot disappearance data for the two experiments. In the top panels of (a) and (b), the frequency of disappearances for a 30-s trial is shown for all conditions. In the bottom panels of (a) and (b) the averaged duration of a single disappearance is shown for each condition. Black bars indicate conditions where the moving stimulus was in front of the dots, grey bars are zero disparity conditions and white bars are conditions in which the moving stimulus was behind the static dots. In (b) the asterisks indicate conditions where there was no induced surface (rotated Kanizsa elements).

19% of that measured in Experiment 1. Thus, the widely spaced Kanizsa elements appear to produce a weaker induced surface than the grid pattern and are thus a less effective motion-induced-blindness stimulus. The discrepancy may be due to a difference in the salience of the induced surface produced in the two experiments. However, our data do not exclude the possibility that local spatial interactions, as outlined above, may also play some role in masking the stationary elements.

3.2. Frequency and duration of dot disappearance

Fig. 3 depicts the individual subject data for all conditions, expressed as the frequency of dot disappearance, i.e. the number of button presses made in a 30-s trial, as well as the average duration of a button press in each condition. As mentioned previously, individual variability was seen in the absolute level of dot disappearance, although the same pattern of disappearance was found across conditions for all subjects (small error bars of Figs. 1(b) and 2(c)). This variability can be seen in Fig. 3 by multiplying the frequency (top panels of (a) and (b)) by the duration (bottom panels).

Fig. 3 shows that in Experiment 1 (Fig. 3(a)), where the grid elements gave rise to a robust surface representation, both frequency and duration were modulated by depth ordering for all subjects. The data of Experiment 2 (Fig. 3(b)) shows a similar trend for the three subjects with the largest disappearance values (ML, PM, WA). Subject BC has the highest frequency and duration of disappearance for the Kanizsa-in-front condition and no real difference for the others; the results of subject EG cannot be predicted by either a change in frequency or duration, but rather as a combination of the two.

4. Conclusion

Overall, our results indicate that motion-induced blindness can be predictably modulated by simple occlusion principles and by surface completion of the moving components in the display. These results add to existing psychophysical findings highlighting the importance of surface completion as a building block for visual perception (Nakayama, He, & Shimojo, 1998). In our stimuli, a modally completed surface (Kanizsa, 1979) induced by the rigid, predictable motion and common disparity of the moving elements acts as a perceptual occluder, masking the static dots. In this respect, the results of Experiment 2 are especially striking, as they demonstrate perceptual interactions between elements that are spatially separated. One possible explanation of this result is that, at some level of representation, a surface defined by a group of local elements or interpolated across space due to surface completion is able to compete for perception with a stationary object that is physically present. As the three stationary elements disappear independently, this would require suppression at a relatively fine level of spatial detail. This suggests a role for surface completion early in the visual pathway where such detail is available. Physiological evidence does exist for surface representation early in visual processing. Surface and object construction have recently been shown in relatively low- and mid-level visual areas of the brain. Low-level visual areas such as V1 and V2 show responses to 3D surface configuration (Bakin, Nakayama, & Gilbert, 2000; Lamme, 1995) and illusory contours (Lee & Nguyen, 2001; Peterhans & von der Heydt, 1989). Bakin et al. reported that neurons in area V2 utilized contextual depth information to integrate occluded contours, signal object boundaries and segment surfaces. Lee and Nguyen (2001) used illusory contour stimuli to modulate cell responses in area V1 where the receptive field either lay along the illusory contour, increasing the firing rate of the neuron, or outside the contour, decreasing the firing rate of the neuron. While feedback from higher areas cannot be eliminated in these studies, the presence of activity in these lower visual areas strongly suggests some role in surface completion.

While the results of the present study have shown the importance of surface interactions to motion-induced blindness, several interesting issues remain regarding the phenomenon. That we were not able to fully eliminate dot disappearance in our study hints that additional factors are involved. The role of motion needs more attention, including the importance of rigidity in the global motion. Recently, Leopold, Wilke, Maier, and Logothetis (2002) have shown that some motion-induced blindness does occur with randomly moving dots (within a single depth plane), indicating that non-rigid motion can drive the phenomenon. Additional investigations into the parameters of the surface structure needed to drive the disappearance are also necessary to fully explain the phenomenon.

The implications of the present study may be generalized beyond motion-induced blindness by comparing it with other examples of visual disappearance. For example, it is interesting to consider the similarity of the motion-induced blindness phenomenon to binocular rivalry. In both cases two objects at the same location are competing for awareness. The interactions between patterns projected to the two eyes in binocular rivalry, or between completed objects in motion-induced blindness might reflect similar strategies employed by the visual system, to suppress otherwise salient features in order to produce a reasonable interpretation of the world.

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