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Perceptual artifacts in random-dot stereograms

Inna Tsirlin, Laurie M Wilcox, Robert S Allison
Centre for Vision Research, York University, 4700 Keele Street, Toronto, Ontario M3J 1P3, Canada;
e-mail: itsirlin@yorku.ca
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Abstract. Unrestricted positioning of elements in random-dot stereograms with steep disparity gradients, such as stereo-transparent stereograms depicting overlaid surfaces, can produce perceptual artifacts similar to disparity noise. It is shown that these artifacts hinder the segregation of overlaid surfaces in transparent random-dot stereograms and thus disrupt the perception of stereo-transparency. This effect is intensified with increases in the overall element density of the stimuli. We outline the origin of this phenomenon and discuss techniques to prevent such artifacts.

1 Introduction

In pseudo-transparent scenes, light passes through gaps in non-transparent lacy objects, such as wire fences or tree branches. Random-dot stereograms (RDSs) can be used to create such percepts based on disparity alone (Julesz 1971). This phenomenon, called stereo-transparency, has ecological and computational importance. In natural environments, pseudo-transparent surfaces, such as overlapping tree branches are abundant in the flora. Stereopsis helps to disambiguate the depth order of the vegetation layers and segregate and localise targets positioned among them. In the computational domain, stereo-transparency poses a difficult problem for models of stereopsis, since there are steep disparity gradients and depth discontinuities nearly everywhere. These properties make stereo-transparency an intriguing phenomenon.

Stereo-transparency has been investigated in a number of psychophysical and computational studies (Akerstrom and Todd 1988; Gepshtein and Cooperman 1998; Lankheet and Palmen 1998; McKee and Verghese 2002; Parker and Yang 1989; Pollard et al 1985; Prazdny 1985; Stevenson et al 1991; Tsai and Victor 2003; Tsirlin et al 2008; Wallace and Mamassian 2004; Weinshall 1989, 1991, 1993). In all psychophysical studies transparent RDSs were used, in which several planes of random elements were overlaid and shifted in depth in order to create the percept of pseudo-transparency. Element placement in such stimuli is an important consideration. Allowing elements from different surfaces to overlap or to be immediately adjacent produces perceptual artifacts, which can potentially disrupt surface segregation. We will refer to these artifacts as ‘mismatched clusters’.

The explanation for the mismatched cluster artifacts lies within the laws of perceptual organisation. In particular, the tendency of the visual system is to group similar objects located in close proximity and to resolve ambiguous stimuli in favour of the simplest configuration. Typically, when transparent RDS stimuli are generated, elements are positioned on each plane first, after which the left and the right copies of the planes are overlaid in the left and the right half-images to create a percept of stereo-transparency. Elements from different planes in an RDS generated this way can overlap or be laterally adjacent. The elements in RDS stimuli are often square owing to the restrictions imposed by the digital representation of images. We consider this type of element here, but other types might be susceptible to similar perceptual artifacts. Mismatched clusters consist of at least two elements: at least one element belongs to the farther plane and at least one to the closer plane (with respect to the observer).

When elements are adjacent to each other or partially overlap, they form a single polygon (see figure 1). Many different configurations of mismatched constructs are possible. The nature of the configurations depends on RDS parameters and the method of generation. For simplicity of exposition, a rectangular two-element cluster in a two-plane transparent RDS will be considered. In this example, a two-element mismatched cluster consists of elements d_c and d_f, which belong to the closer and the farther planes with respect to the observer. Their corresponding copies in the left and the right stereo-images are $d_{c,l}$, $d_{c,r}$ and $d_{f,l}$, $d_{f,r}$. If in the left stereo-image $d_{f,l}$ and $d_{c,l}$ are adjacent or overlap they merge and form a rectangle. In the right stereo-image, to create a percept of depth, $d_{f,r}$ is shifted by disparity k with respect to $d_{f,l}$. When k is sufficiently small, such that $d_{c,r}$ and $d_{f,r}$ still overlap or are adjacent, then the rectangle formed by $d_{f,l}$ and $d_{c,l}$ in the left stereo-image now will be matched to the rectangle formed by $d_{c,r}$ and $d_{f,r}$ in the right stereo-image. However, the disparity of the resulting rectangle will be less than k and it will appear to float in between the two surfaces. When k is smaller than the width of the two elements, the rectangles will have different widths in the two half-images and consequently will appear slanted when fused. Figure 1 shows a schematic representation of the above example.

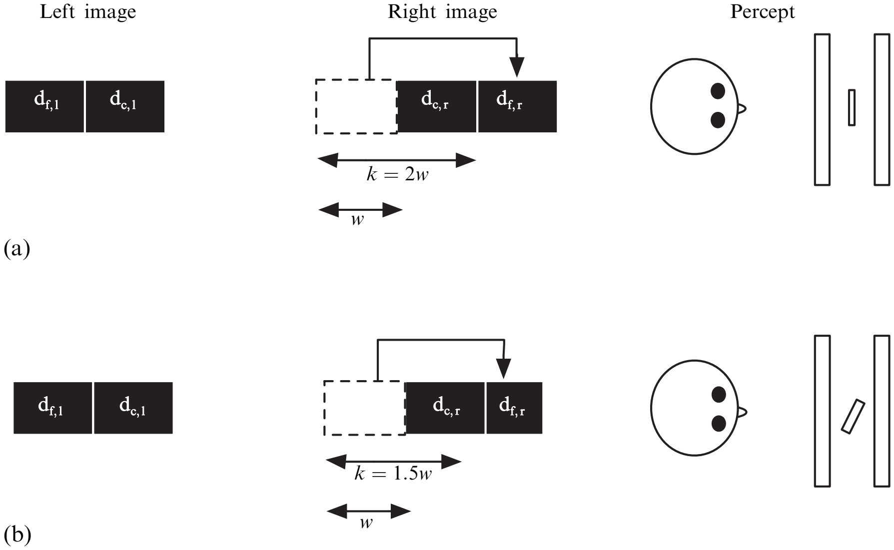

Figure 1. A schematic representation of a simple configuration of mismatched clusters. Left copies of the elements $d_{f,l}$ and $d_{c,l}$ are adjacent to each other and form a rectangular shape. In the right stereo-image, $d_{f,r}$, the copy of the element belonging to the far surface is shifted by k to create a percept of depth. After the shift, $d_{f,r}$ and $d_{c,r}$ are still adjacent but have exchanged order. In (a) k is equal to twice the width of the elements, denoted by w, so that the rectangle formed by $d_{c,r}$ and $d_{f,r}$ is of the same width as the one formed by $d_{f,l}$ and $d_{c,l}$ and is shifted by w. Hence when the stereogram is fused the rectangle appears to float in the middle between the front and the back surfaces as shown in the right top panel of the figure. In (b) k is equal to $1.5w$ so that the rectangle formed by $d_{f,r}$ and $d_{c,r}$ is narrower than the one formed by $d_{f,l}$ and $d_{c,l}$. When the stereogram is fused the rectangle appears to be slanted as shown in the right bottom panel of the figure.

In this simple example the disparity shift is shown in only one image. Similar perceptual artifacts appear when the elements are shifted by half the disparity in opposite directions in the two eyes.

Mismatched clusters have not been discussed in the literature dealing with stereo-transparency, although they might have been present in the stimuli used in some studies. For example, Weinshall in her work on stereo-transparency (Weinshall 1989, 1991, 1993) reported several phenomena, which are likely attributable to mismatched clusters:

> "When looking at stereograms with transparent layers ambiguous or not ambiguous, subjects reported seeing points floating in a range of depth values. ....One subject identified a layer at an intermediate depth value between the two dense layers." (Weinshall 1991)

When present in a transparent RDS, mismatched clusters could create a percept of a thick volume of elements rather than that of two segregated surfaces, similar to the percepts observed at small inter-plane disparities (Parker and Yang 1989) or with addition of disparity noise (Palmisano et al 2001). Moreover, the density of the planes at the intended depths will be reduced, resulting in a corresponding loss of surface integrity. Essentially, mismatched clusters may act like a form of disparity noise by disrupting the segregation of overlaid surfaces; however, this has not yet been established empirically. To do so, we have measured the depth separation between overlaid RDS surfaces required for the perception of stereo-transparency in stimuli with and without mismatched clusters.

It is likely that the number and the nature of mismatched clusters, and consequently their effect on perception, is modulated by a variety of stimulus parameters. For example, changes in inter-plane separation should affect the slant of mismatched constructs (consider figure 1b). Perhaps more significantly, increasing the density of RDS elements results in an increase in the probability of their adjacency or overlap. This should, in turn, increase the number of mismatched clusters. Given that element density is a common experimental manipulation in studies of stereo-transparency, we also investigated the impact of density on the occurrence and consequences of mismatched clusters.

2 Methods

2.1 *Observers*

Four experienced observers participated in this study: two experimenters and two observers naive as to the goals of the experiment. All observers had normal or corrected-to-normal visual acuity and good stereoacuity.

2.2 *Apparatus*

Scripts for stimulus generation and presentation were created and executed on a G4 Power Macintosh using Python 2.3 and OpenGL libraries for Python, under Mac OS X 10.3. Stimuli were presented on a pair of CRT monitors (Clinton DS2000HB, 14.25 inches × 10.7 inches) viewed through a mirror stereoscope with a viewing distance of 0.6 m. Luminance of the CRT monitors was measured with a Konika Minolta LS-110 photometer and linearised in the software. The resolution of the monitors was set to 1024 × 768 pixels and the refresh rate to 100 Hz. At this resolution and viewing distance, each pixel subtended 1.9 min of visual angle. Observers used a chin-rest to stabilise head position during testing.

2.3 *Stimuli*

Stimuli were 12.6 deg × 12.6 deg RDSs, where each element was 7.6 min of arc × 7.6 min of arc square. In a given session, the overall element density was either 9.4, 18.9, or 28.3 dots deg^{-2}. The average luminance of the stimuli was 10 cd m^{-2} and the Michelson contrast was 99%. The plane of the RDS closest to the observer was presented at the screen depth and the second was presented with uncrossed disparity with respect to the screen (elements were shifted by half the disparity in opposite directions in each stereo-pair). When the depth between the planes was adjusted, the back plane moved relative to the front plane.

We compared responses to two types of stimuli. In the mismatched clusters condition (MC) the stimuli were generated without any positional restrictions between planes.

First, elements were separately positioned on two planes (elements did not overlap within one plane but could be adjacent), and then the left and right copies of the planes were overlaid to form the right and the left stereo half-images. When these stereograms were fused, mismatched clusters appeared. In the no mismatched clusters condition (NM), the positioning of the elements on different planes was restricted such that no overlap or adjacency among elements was allowed (see figure 2). When the observers fused these stimuli they did not perceive any mismatched clusters.

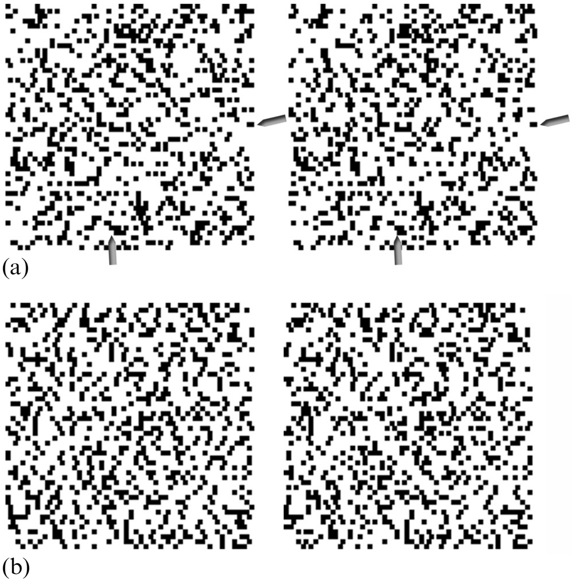

Figure 2. Examples of stimuli arranged for crossed fusion. (a) An RDS generated without restricting the positions of the elements between surfaces. When fused, multiple mismatched clusters are perceived. The grey arrows point to examples of mismatched clusters: slanted (bottom) and floating (right). (b) An RDS generated with restricted positioning of the elements, such that lateral adjacency or overlap of elements from different surfaces is not permitted. When these stereo-pairs are fused, no mismatched clusters are observed.

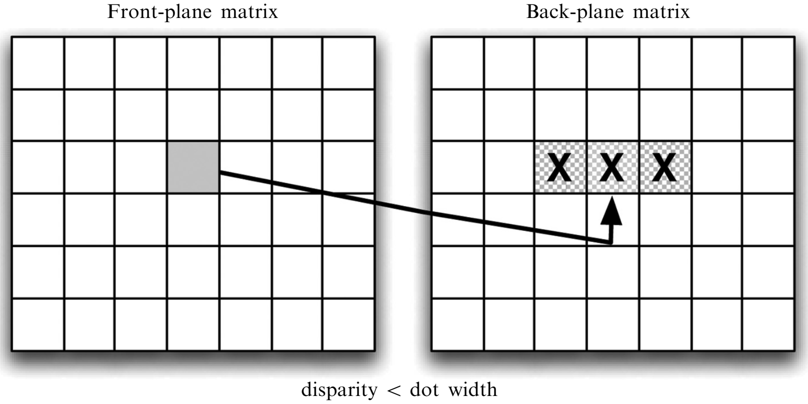

Figure 3. Illustration of the positioning algorithm. First, a position (cell) is selected from the front-plane matrix. Next, positions in the back-plane matrix that were calculated to overlap (or abut) the front surface dot in the half-images at a given disparity are marked as invalid. In this case, the disparity is smaller than dot width, so the same position as well as its immediate neighbours are marked as invalid in the back-plane matrix. If dots were to be placed in these positions, they would overlap with the front-plane dot in both or one of the half-images.

To generate the second type of stimuli we used the following algorithm. Each plane in the RDS was represented as a 2-D matrix where each cell could contain a single element. The size of the cells was equal to the size of the elements. Starting at the front plane, each matrix was populated by randomly selecting element positions, without replacement. When a position was selected in the front plane, locations in the back plane that were calculated to overlap (or abut) the front surface element in the half-image at the given disparity were marked as invalid. Dot positions for elements in the back plane were selected randomly, without replacement, from the remaining valid positions in the back-plane matrix (see figure 3).

2.4 *Procedure*

Observers were shown RDS stimuli depicting two overlaid planes. At the beginning of each trial, the planes had either zero relative disparity and appeared as a single plane, or they were separated by a relatively large disparity of 7.6 min of arc which created a percept of well-segregated planes. The observers were asked to adjust the depth separation between the planes until a coherent percept of pseudo-transparency was achieved or was just lost, depending on the starting point of the trial. The observers adjusted the relative depth until they could clearly distinguish two separate surfaces as opposed to just being able to discriminate differences in the depth of the stimulus elements (which can be perceived at very small depth separations). To assist the observers in their judgments, before testing the observers were shown several examples of well-segregated stereo-transparent RDSs. Observers used key presses to adjust the inter-plane disparity in steps of 22.8 min of arc. After each adjustment, the RDS elements were repositioned (ie a different random sample of element locations) and redrawn. Observers were allowed to shift their gaze freely during a trial and had unlimited viewing time. Subjects participated in three sessions, one for each density level. The ordering of these sessions was counterbalanced across subjects. Each session consisted of 20 MC and 20 NM trials, presented in random order.

3 Results

Figure 4 shows the inter-plane disparity required to perceive stereo-transparency in MC and NM conditions and figure 5 shows the mean differences between the two conditions for the three stimulus densities. Repeated-measures ANOVA was performed on the data with condition and density as within-observers factors. As anticipated, significantly smaller depth separations supported stereo-transparency in the NM condition than in the MC condition (main effect of condition $F_{1,76} = 566.03$, $p < 0.001$).

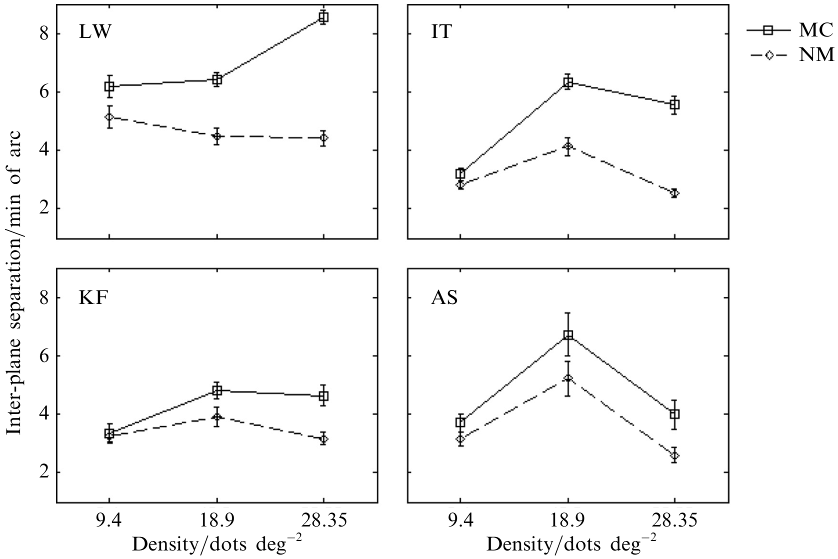

Figure 4. Disparity required for perception of stereo-transparency as a function of density and stimulus condition for four observers. Data for the mismatched cluster conditions (MC) are shown with solid lines and open squares and data for the no mismatched cluster conditions (NM) are shown as dashed lines and open diamonds. The error bars show the 95% confidence intervals.

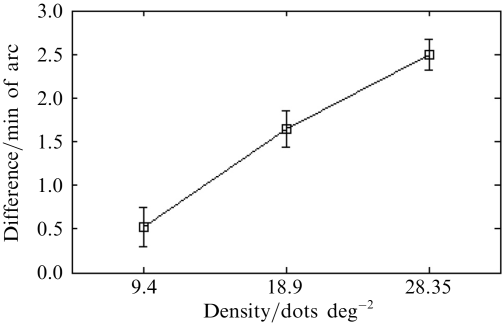

Figure 5. Mean difference in inter-plane disparity between the MC and NM conditions. The error bars show the 95% confidence intervals which were generated from the ANOVA model.

Moreover, this difference increased with the increase in density (significant interaction effect between density and condition $F_{2,152} = 106.4$, $p < 0.001$). All observers showed the smallest difference between the MC and NM conditions for stimuli with the lowest density of 9.4 dots deg^{-2} and three of the four observers showed the largest condition effect at the largest density of 28.3 dots deg^{-2} (observer AS showed the largest condition effect at the intermediate density). Separate t-tests with Bonferroni correction confirmed that MC settings were significantly greater than NM settings for all densities and all observers except for observer KF at the lowest density ($t_{19} = 0.637$, $p = 0.532$). These data indicate that mismatched clusters degrade the percept of stereo-transparency and that this effect intensifies with increase in stimulus density.

4 Discussion

Our data show that the presence of mismatched clusters in a fused RDS degrades perception of stereo-transparency. In natural scenes, opaque overlapping elements in pseudo-transparent surfaces can merge owing to stereoscopic image formation as in the MC condition. This should give rise to mismatched clusters and may contribute to the difficulty in perceiving pseudo-transparency in the absence of monocular cues to surface segregation. When a study aims to replicate these conditions, mismatched clusters could be preserved in random-dot stimuli to maintain external validity. It should be noted, however, that in natural scenes, disparity information would be typically accompanied by variations in colour, texture, shading, and other depth cues that would aid either in binocular matching or in surface segregation. If the objective is to study fundamental properties of neural mechanisms, mismatched clusters should be taken into account. In such cases, the presence of mismatched clusters poses a potential problem since, as was shown here, such artifacts disrupt the segregation of transparent planes. Moreover, if not controlled, these constructs can introduce spurious dependences in the data when stimulus attributes, such as element density, are manipulated in the experimental design. Mismatched clusters can occur in a wide variety of random-element stereograms but are particularly an issue with rectangular elements, which can merge to form rectangular blocks. Several techniques exist which can prevent the emergence of the mismatched clusters in transparent RDS stimuli with rectangular elements. One approach was used by Parker and Yang (1989). They divided their stereogram into rows of a fixed height and applied the same disparity to elements along a row. All elements in even rows belonged to one disparity plane while all elements in odd rows belonged to the second disparity plane. Because all elements in one row were offset in the same direction, no mismatched clusters of the sort described here would have been created. This approach is simple, but it imposes a fairly strict order on the arrangement of the elements, which might not be suitable for all paradigms. An alternative less-restrictive technique of elements positioning is described in section 2.

Stevenson et al (1991) segregated presentation of disparate random-dot planes in time, on alternate video frames. When alternation rate is sufficiently high, as in their experiments, the luminance of overlapping elements sums linearly rather than flickers. Summing the luminance of the overlapping elements in the RDS would reduce the occurrence of mismatched constructs by providing an additional disparity cue to surface segregation, namely the luminance edges of the individual overlapping elements. In this sense, the technique of summing dot planes is similar to translucency where the background elements are visible through the foreground (although attenuated rather than summed as in the temporal-integration stimuli). In contrast, the MC conditions in the current experiment simulated the more common pseudo-transparent situation characterised by partial occlusion of the background by foreground structure [see more detailed discussion of transparency types in Tsirlin et al (2008)].

In summary, we have presented evidence that unrestricted positioning of elements in stereograms with overlaid surfaces results in perceptual artifacts, which hinder the perception of stereo-transparency. We have also shown that the effect of these artifacts is modulated by stimulus properties such as density. Researchers studying stereo-transparency as well as using other random-dot stimuli with steep disparity gradients should be aware of such artifacts and, when necessary, use techniques to avoid them and ensure accurate measurement of perceptual phenomena.

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