Stereoscopic transparency: Constraints on the perception of multiple surfaces

Inna Tsirlin Center for Vision Research, York University, Toronto, ON, Canada

Robert S. Allison Center for Vision Research, York University, Toronto, ON, Canada

Laurie M. Wilcox Center for Vision Research, York University, Toronto, ON, Canada

Stereo-transparency is an intriguing, but not well-understood, phenomenon. In the present experiment, we simultaneously manipulated the number of overlaid planes, density of elements, and depth separation between the planes in random dot stereograms to evaluate the constraints on stereoscopic transparency. We used a novel task involving identification of patterned planes among the planes constituting the stimulus. Our data show that observers are capable of segregating up to six simultaneous overlaid surfaces. Increases in element density or number of planes have a detrimental effect on the transparency percept. The effect of increasing the inter-plane disparity is strongly influenced by other stimulus parameters. This latter result can explain a difference in the literature concerning the role of inter-plane disparity in perception of stereo-transparency. We argue that the effects of stimuli parameters on the transparency percept can be accounted for not only by inhibitory interactions, as has been suggested, but also by the inherent properties of disparity detectors.

Keywords: stereopsis, stereo-transparency, pseudo-transparency, neural interactions, size-disparity correlation

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Introduction

Transparency is an integral part of our reality as many objects in the world are fully or partially transparent. We can identify three primary different types of transparency (see Figure 1):

1. Glass-transparency—light passes through objects made of clear transparent materials such as glass.
2. Translucency—translucent materials allow light to pass through them only diffusely and cannot be clearly seen through. Examples of such materials are frosted glass and certain types of cloth.
3. Pseudo-transparency—light passes through gaps in non-transparent lacy objects such as wire fences or tree branches.

In natural environments, pseudo-transparency occurs frequently in the flora. Perception of such pseudo-transparent surfaces would have been vital for our ancestors since their survival depended on the ability of their visual systems to detect a predator or a potential meal hiding in the vegetation. To identify such targets, they would have had to segregate multiple overlaid pseudo-transparent surfaces created by tree branches or leaves. Stereopsis plays an important role in this process by providing the necessary information about the depth order of surfaces and the magnitude of the depth difference between them.

Previous psychophysical experiments have shown that pseudo-transparency can be perceived in surfaces defined solely by disparity (Julesz, 1971). This phenomenon is known as stereo-transparency. Stereo-transparency represents an extreme case of depth discontinuities or the thin structure problem as the disparity field is discontinuous nearly everywhere. Thus, it is not only ecologically relevant but it also poses a challenge for computational theories of stereopsis. Despite the potential importance of stereo-transparency, the psychophysical literature on the phenomenon is sparse. It has been shown that observers are capable of perceiving two overlaid transparent planes in unambiguous random dot stereograms (RDS) (Akerstrom & Todd, 1988; Gepshtein & Cooperman, 1998; McKee & Verghese, 2002; Parker & Yang, 1989; Wallace & Mamassian, 2004) and up to four planes in ambiguous stimuli, where the elements are repeated, allowing more than one possible matching solution (Weinshall, 1989, 1991, 1993). Compared with perception of opaque surfaces, perception of transparent surfaces requires longer presentation times and is more difficult to establish reliably (Akerstrom & Todd, 1988; Wallace & Mamassian, 2004). It has also been reported that increases in element density have a detrimental effect on observers' ability to resolve stereo-transparency (Akerstrom & Todd, 1988; Gepshtein

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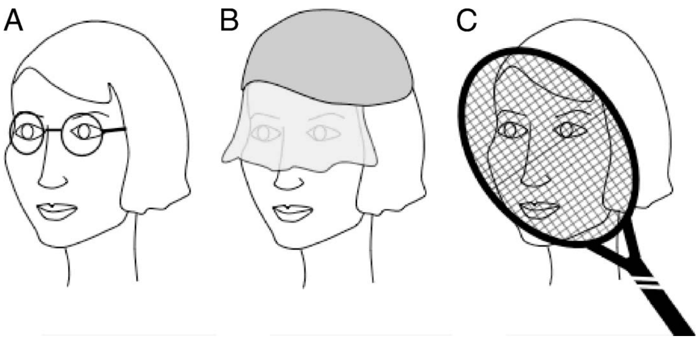

Figure 1. Types of transparency. (A) Glass transparency. (B) Translucency. (C) Pseudo-transparency.

& Cooperman, 1998; Wallace & Mamassian, 2004). However, the literature provides variable reports about the perceptual effects of changes in the relative disparity between two overlaid planes. Akerstrom and Todd (1988) and Gepshtein and Cooperman (1998) observed that increasing the separation in stereoscopic depth between two overlaid planes degrades the transparency percept. Wallace and Mamassian (2004) found no such effect.

In the present work, we use a novel paradigm to determine the constraints on the perception of stereo-transparency. We first establish the number of overlaid pseudo-transparent surfaces that can be perceived in a single stereogram from binocular disparity alone. Next, we determine the separate and the combined effects of the number of planes, element density, and inter-plane disparity on the perception of stereo-transparency. Unlike previous experiments, we use a task that ensures that observers cannot respond on the basis of the relative locations of single elements.

Methods

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″ × 10.7″) arranged in a mirror stereoscope with a viewing distance of 0.6 m. The monitors were calibrated to compensate for curvature. 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′ of visual angle. Observers used a chin rest to stabilize head position during testing.

Observers

Three experienced observers IT, YS, and TB (20–29 years of age) participated in the experiment. IT was an author, and the other two were naive as to the purpose of the study. All observers had normal or corrected-to-normal visual acuity and good stereo acuity.

Stimuli

Stimuli were 12.6 × 12.6° RDS, where each element was 7.6 × 7.6′. The average luminance of the stimuli was 10 cd/m^2, and the Michelson contrast was 99%. Each stereogram, when fused, depicted several overlaid planes of dots. The first plane (closest to the observer) was presented at fixation, and the rest were presented with uncrossed disparities with respect to fixation. Each adjacent pair of planes was separated in depth by disparity d (see Figure 2). Antialiasing was used to allow subpixel positioning.

Dot positions were randomly assigned but no overlap or horizontal adjacency of dots across planes was allowed. The following algorithm was used to position the dots. Each plane in the RDS was represented as a 2D array where each cell could contain a dot (i.e., each array was a subimage corresponding to the dots for the specific plane). Starting at the fixation plane, each array was populated by randomly selecting positions for dots among those that were not marked as occupied or invalid. When a position was selected, it was marked as occupied in arrays for both the plane where the dot was placed and in all the other transparent planes. Additionally, in the other planes, the two positions to the left and to the right of the newly occupied position were marked as invalid. This exclusion took into account the disparity shift and thus precluded overlap or horizontal adjacency of dots across planes. This procedure was repeated for all the planes in the RDS.

Glass patterns

The main objective of the current experiment was to clarify the constraints on stereo-transparent surface perception. Consequently, it was vital that we design a task

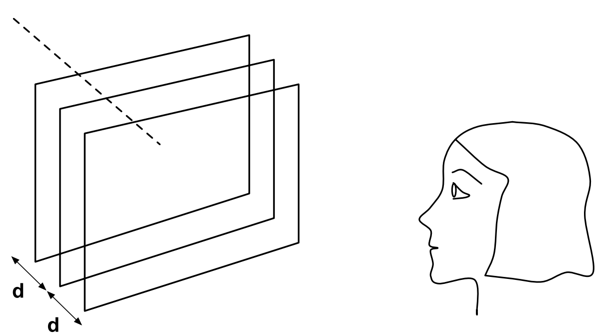

Figure 2. Graphical representation of a multi-plane stimulus. The observer is viewing a stereogram of several superimposed planes with inter-plane depth separation d. The dashed line shows that there may be more overlaid planes.

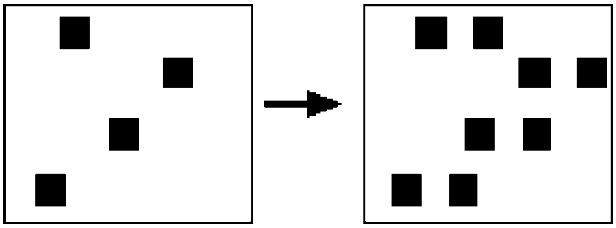

Figure 3. Creating a horizontal-shift Glass pattern. The first half of the dots is copied and translated horizontally such that there is a gap of 7.6′ (four pixels) between the elements of each pair.

that forced the observers to perceive coherent pseudo-transparent planes rather than individual dots floating at different depths. To assess the percept of surface coherency, we used a task that required subjects to determine whether Glass patterns (Glass, 1969) were present in one or more of the transparent planes. In Glass pattern planes, which we will refer to as Glass planes, dots were arranged in a horizontal-shift Glass pattern. Glass planes were created in the same manner as the other planes but only one half of the dots in the plane were randomly positioned; the other half of the dot positions were obtained by copying the first half and translating the copy horizontally such that there was a gap of 7.6′ between the elements of each pair (see Figure 3). The number and the depth order of Glass planes were selected randomly, such that for an RDS with n planes the number of Glass planes was in the range $[0, n]$.

On each trial, observers were asked to report the total number of planes in the RDS and how many of these were Glass planes. As in previous studies of stereo-transparency (Akerstrom & Todd, 1988; Parker & Yang, 1989; Wallace & Mamassian, 2004; Weinshall, 1989, 1991, 1993), the first part of this task could have been performed by enumerating single elements at different disparities. However, in order to correctly identify a plane of dots as a Glass plane, the observer had to detect a pattern within the organization of the plane. That is, both local and global pooling had to take place (Dakin & Bex, 2002; Wilson & Wilkinson, 1998). This required proper segregation of overlaid surfaces since noise dots from other planes erroneously assigned to the Glass plane would have disrupted the pattern. It can be argued that the presence of one or more Glass patterns could have been detected monocularly. However, without proper segregation of the surfaces in depth subjects could not accurately report the number of Glass planes.

Stimuli parameters

The number of overlaid planes, element density, and inter-plane depth separation (disparity) were varied factorially as follows:

Number of planes: 2, 3, 4, 5, or 6.

Density: 1.8, 6.2, 10.6, and 15.6 dots/deg^2. When new planes were added to an RDS with a certain density, the overall density was kept constant. The dots were simply redistributed across the planes.

Inter-plane disparity: 1.9′, 3.8′, 5.7′, or 7.6′. Total disparities per RDS (inter-plane disparities summed up) fell into the range 1.9′–38′, which is well within the fusional range (Howard, 2002).

Overall, there were 80 different experimental conditions (4 density $\times$ 4 disparity $\times$ 5 number of planes; Figure 4).

Procedure

The experiment was run over 20 sessions for observers IT and YS and 10 sessions for observer TB, where each session included two repetitions of each condition for a total of 160 trials per session. In each session, the trials were presented in random order. A square, 26′ fixation pattern was presented at zero disparity before each trial to allow observers to adjust their vergence.

Once the observers fixated on the pattern, they pressed a button to display the stimulus. Observers viewed the stimulus for 3 (observers IT and YS) or 5 (observer TB) seconds after which they reported the total number of planes and the number of Glass planes they perceived by pressing the appropriate buttons on a gamepad. The fixation pattern was absent during the presentation of the stimulus. In light of the long presentation times, observers were able to change fixation and vergence while viewing the stimulus. Akerstrom and Todd (1988) proposed that the long presentation times required to perceive stereo-transparency reflect the importance of vergence eye movements for the task. We repeated the experiment with one observer, who maintained fixation throughout the trials. The results were similar to the main findings but prolonged fixation caused discomfort from eyestrain.

Figure 4. Sample stimulus. Stereo pair consisting of two overlaid planes: a Glass plane at fixation and a random plane at an uncrossed disparity of 7.6′. The overall density is 16.7 dots/deg^2. Cross-fuse the white squares on the top to view the stereogram. For presentation purposes, this example was made smaller than the actual stimuli used in the experiment.

Statistical analysis

Logistic regression analysis was performed on the data. Logistic regression describes the relationship between a dichotomous response variable and a set of explanatory variables. The dichotomous response variable in our logistic regression model was the veracity of the observers' response (both number of planes and number of Glass planes specified correctly). Explanatory variables in the model were the number of planes, density, disparity, observers, and interactions of stimulus parameters (density and disparity, disparity and number of planes, etc.).

Results

In Figure 5, percent correct is plotted as a function of each of the stimulus parameters described above. Note that a response was counted as correct when the observer indicated *both* the correct number of planes and the correct number of Glass planes. It was necessary to combine the two tasks since the number of Glass planes task served as a check for the coherency of the perceived pseudo-transparent planes. Separate analysis of the two judgments confirmed the main findings. Logistic regression analysis showed that subject, number of planes, disparity, density, combination of density and disparity, and combination of planes and disparity influenced performance significantly.

Number of planes

The general effect of the manipulation of the number of planes was clear. Data for all observers (see Figure 5) showed that an increase in the number of planes caused a decrease in performance (Wald $\chi^2 = 1603.66$; $p < .000$; $df = 4$; Exp(B) for indicator categorical contrasts with the performance with two-plane stimuli as reference were 3 planes = .253, 4 planes = .055, 5 planes = .016, 6 planes = .007). However, determining an upper limit on the number of overlaid planes that can be perceived simultaneously requires careful analysis. Recall that the experimental task consisted of two parts: stating the number of planes (NP task) and the number of Glass planes (NGP task) in the stimulus. Both responses had to be correct for a trial to be scored as successful. To determine the upper limit on performance, we first had to define chance level for this task. There were five possible answers in the NP task, thus the corresponding chance level was 1/5 or 20%. However, even when the observers were incorrect, they were close to the true number of planes. For example, when viewing two or three planes, they were very unlikely to respond five or six. This is evident in Figure 6, which shows the distributions of the observers' responses to the NP task, for stimuli with different numbers of planes. The maxima of the distributions are always located at the correct answer. Moreover, the distributions have substantial values only in immediate proximity of the maxima (two neighboring values). Based on these observations, we defined the neighborhood of any given number of planes n as the set $\{n - 1, n, n + 1\}$ (for marginal cases the neighborhood is defined as $\{n, n + 1, n + 2\}$ and $\{n - 2, n - 1, n\}$, respectively). It is apparent from Figure 6 that vast majority of the answers (100–84%) for each type of stimuli with n planes, falls within the respective neighborhood of n as defined above. Consequently, the number of possible answers in the NP task is effectively reduced from five to three, the size of the neighborhood. Thus, we set the chance level of performance for the NP task to 1/3 or 33%.

The possible answers for the NGP task were bound by the perceived number of planes pn since the observers knew that the number of Glass planes fell into the interval $[0, pn]$. Since the smallest pn present in the stimuli was two, the smallest number of possible answers for the NGP task was three. This implies that the chance level of performance for the NGP task was always equal to or smaller than 1/3 or 33%. In order to judge performance conservatively on the NGP task, the highest of the levels of chance performance has to be taken. Recognizing that the NGP task was subordinate to the NP task, we set the chance level of performance on the overall experimental task to 33% and the criterion for successful performance to 66%, which is halfway between chance and perfect performance. According to this criterion, as Figure 5 shows, the observers were able to perceive up to three planes under almost all conditions. Under optimal conditions, including low density and high disparity, observers were able to perceive up to six overlaid planes.

Density

Analysis of the data showed (see Figure 5) that for most stimuli increasing element density degraded performance (Wald $\chi^2 = 250.9$; $p < .000$; $df = 1$; Exp(B) = .907). In conditions for which the effect of density cannot be observed, the overall performance was either near perfect (ceiling effect) or almost at chance levels (floor effect).

Inter-plane disparity

The effect of disparity was more complex (Wald $\chi^2 = 32.37$; $p < .000$; $df = 3$). The smallest inter-plane disparity, of 1.9′, corresponded to the poorest performance for all stimuli (see Figure 5). Initial increases in inter-plane disparity resulted in improved performance.

However, in some stimuli, further increase in the depth separation between planes, beyond a certain disparity (hereafter called the peak disparity), degraded performance. We will return to this issue in the following section and in the Discussion.

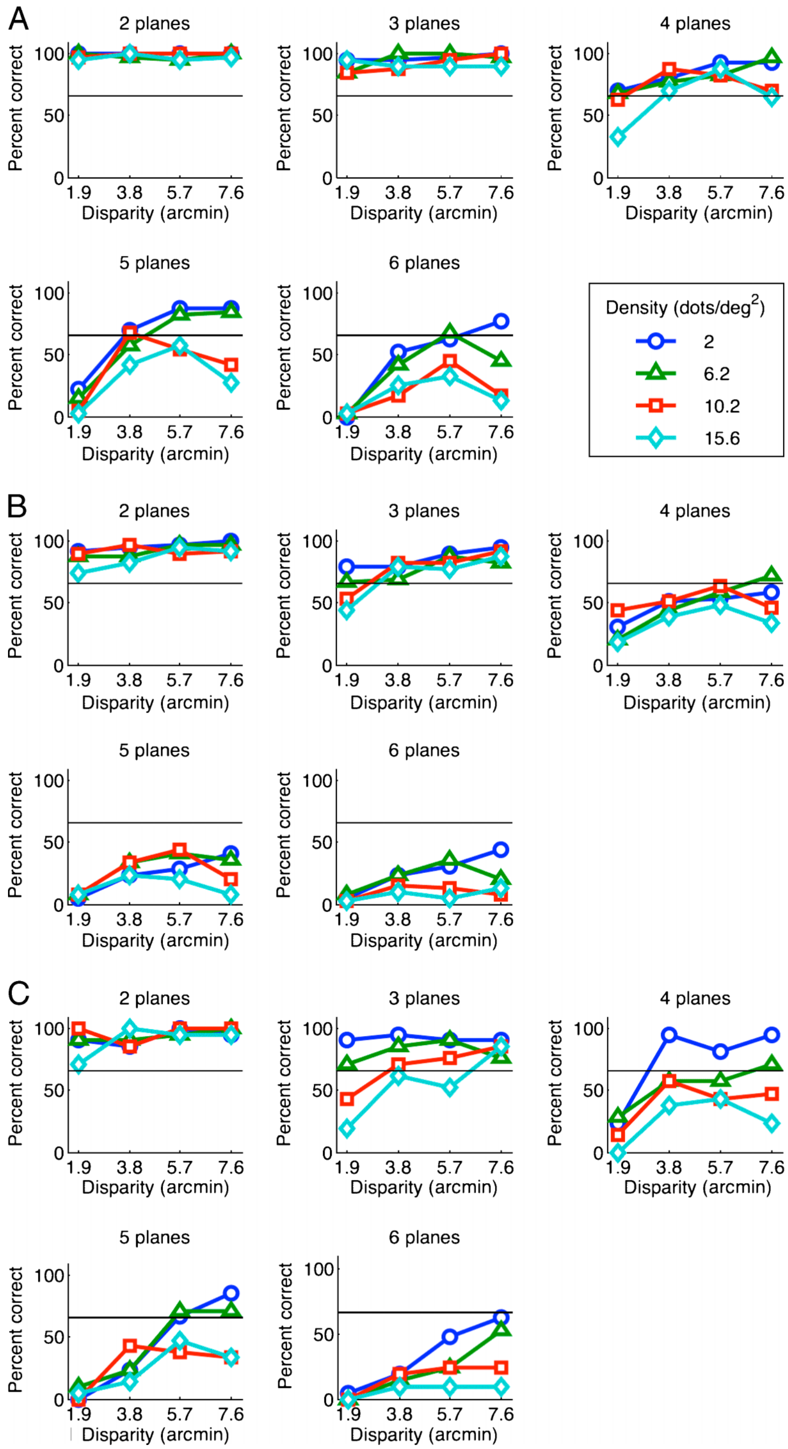

Figure 5. Experimental results for three observers (A) IT, (B) YS, and (C) TB. Each graph corresponds to a different number of planes in the stimulus. In each graph, percent correct is plotted as a function of inter-plane disparity, and each function corresponds to a different density. The horizontal black lines indicate threshold performance (see Results section for details).

Determinants of peak disparity

Polynomial contrasts over disparity in the logistic regression were used to evaluate the interactions of density, number of planes, and disparity underlying the peak disparity and the inverted u-shaped disparity profiles observed for some conditions.

The effect of disparity was strongly influenced by element density as reflected in a significant disparity by density interaction (Wald $\chi^2 = 44.215$; $p < .000$; $df = 3$).

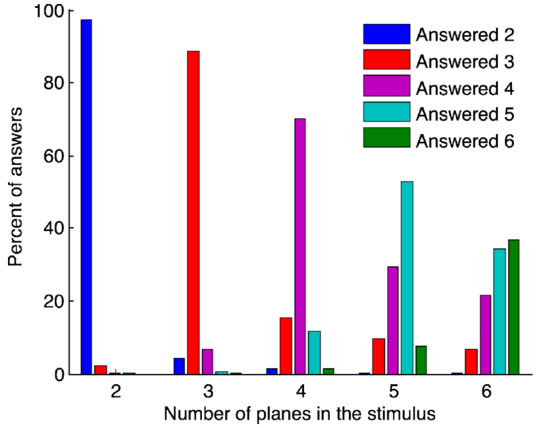

Figure 6. Distribution of observers' responses in the number of planes task. The data for the three observers were combined in this graph. The bars represent the percent of answers given to the number of planes task. The abscissa represents the stimuli with different numbers of planes.

Specifically, peak disparity was smaller for dense stimuli than for sparse stimuli (for stimuli with the smallest density, the peak disparity presumably falls outside the range of disparities tested here). Moreover, the curvature of the plots of percent correct with respect to disparity increased and thus became more peaked with increasing density. This was reflected in a significant negatively signed interaction effect between the quadratic terms of the polynomial contrast of disparity and density (Wald $\chi^2 = 24.318$; $p < .000$; $df = 1$; Exp(B) = .942). Peak disparity was also tied to the number of planes (Wald $\chi^2 = 78.717$; $p < .000$; $df = 12$). As shown in Figure 5, for all subjects the peak disparity phenomenon was not evident for two- and three-plane stimuli. Moreover, for subjects IT and YS, the peak disparity for densities 15.6 dots/deg^2 and 10.6 dots/deg^2 was first apparent in stimuli with four planes while the peak disparity for 6.2 dots/deg^2 density was first apparent in five-plane stimuli. Quadratic terms of the polynomial contrasts of disparity confirmed that the increase in the number of planes increased the curvature of the performance curve with respect to disparity (B values for 4 planes = −.722, 5 planes = −1.410, 6 planes = −1.531).

Overall disparity

In our experimental design, increases in the number of planes resulted in increases in the overall disparity of the stimulus. Therefore, the detrimental effect of the number of planes could also be attributed to the overall disparity. In Figure 7, we plotted the percent correct as a function of overall disparity and the number of planes, where each data point represents the performance pooled over subjects and density. If the overall disparity were the determining factor, the data should overlap and peak at the same overall disparity. Instead, it is clear from Figure 7 that the data differentiated according to the number of planes, suggesting that the number of planes had an effect on transparency perception that was separable from the effect of disparity.

Disparity gradient

The simultaneous manipulation of density and disparity necessarily resulted in concurrent changes in the disparity gradient across conditions. Given the influence of disparity gradients on stereoscopic depth perception (Burt & Julesz, 1980), we reanalyzed the data to evaluate the role they played in our study. Disparity gradients were calculated as the ratio of the largest disparity difference between two planes (the depth difference between the front and the back planes) and the average distance between the elements on these planes. The average distance for each stimulus configuration was computed as:

$$\bar{d} = \sqrt{\frac{p \times a_s}{2 \times n \times a_d}}, \tag{1}$$

where a_s and a_d are the areas of the RDS and a single dot respectively, p is the number of planes, and n is the number of elements in an RDS given a certain density. Figure 8 shows that for a wide range of disparity gradients performance clearly decreased with increasing number of planes, irrespective of the disparity gradient. Therefore, violation of the disparity gradient limit cannot explain the loss of segregation ability that occurred as the number of superimposed planes increased.

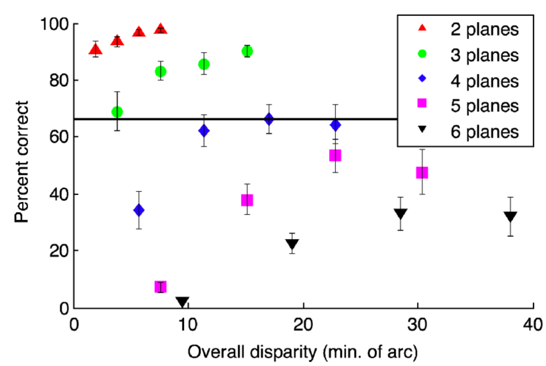

Figure 7. Data (shown in Figure 5) re-plotted as a function of overall disparity. Percent correct is plotted on the ordinate, and overall disparity is on the abscissa. Differently colored data points correspond to different numbers of planes. Each data point represents performance averaged over subjects and density for stimuli with a particular number of planes and inter-plane disparity. The horizontal black line indicates threshold performance (see Results section for details).

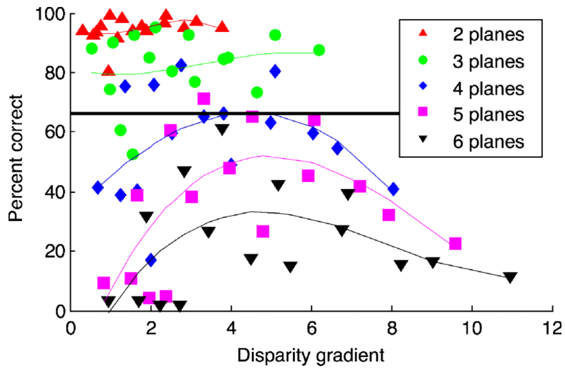

Figure 8. Data (shown in Figure 5) re-plotted as a function of disparity gradients. Percent correct is plotted on the ordinate, and disparity gradients are on the abscissa. Differently colored data points correspond to different numbers of planes. Each data point represents the average performance of the subjects in one stimulus configuration. Error bars were omitted to avoid clutter. The data for stimuli with a particular number of planes were fit with polynomial curves (third-order), which are shown as solid lines of the corresponding color. The horizontal black line indicates threshold performance (see Results section for details).

Per-plane density

Another factor that might account for the detrimental effect of the increase in the number of planes is the decrease in the per-plane density as new planes were added to an RDS. Since the overall density of the stimuli was kept constant as new planes were added, the per-plane density decreased, possibly degrading surface coherency. This could disrupt the percept of transparent surfaces. In Figure 9, we plotted the percent correct as a function of per-plane density and the number of planes, where each data point represents the performance pooled over subjects and disparity. From the figure, it is clear that with similar per-plane densities the performance decreases as the number of planes increases. Consequently, per-plane density alone cannot account for the detrimental effect of increasing the number of planes.

Discussion

In this study, we examined the maximum number of overlaid planes that can be perceived in RDS stimuli and the separate and the combined effects of the number of planes, density, and disparity on the perception of stereo-transparency.

Number of planes

Increasing the number of planes had a detrimental effect on surface segregation. This effect was separate from the losses due to inter-plane or overall disparity. Nor can increases in the number of potential matches for each element account for this effect; in our study, the density of elements was kept constant as new planes were added. Hence, the number of potential matches remained the same for all stimuli with the same density. Any effect of matching noise must be differentially influencing transparent stimuli with increasing numbers of planes (see following section). Loss of surface coherency due to decreasing per-plane density is also not the cause of the degradation of the transparency percept with increase in the number of planes. Furthermore, as shown in Figure 8 above, this effect is not a simple function of the disparity gradients present in the stimuli.

It seems more likely that the deterioration of transparency perception with increasing number of planes is related to higher-level processes. Greenwood and Edwards (2006) attempted to establish the upper limit on the number of discernible transparent-motion signals. They proposed that the limit of three they found was a hard limit imposed by the capacities of visual attention or short-term visual memory. It has been shown that observers are able to track attentively up to five items simultaneously on a single surface (Pylyshyn & Storm, 1988) and up to seven items when they are distributed in depth (Viswanathan & Mingolla, 2002). The capacity of short-term visual memory was found to decrease with increases in the information load of the stimulus (Alvarez & Cavanagh, 2004; Wilken & Ma, 2004). In one study, two to three items were retained for complex stimuli and four to five items could be stored for simpler stimuli (Alvarez & Cavanagh, 2004). If we assume that increasing the density of elements defining our RDSs is one way of increasing complexity, the results of Alvarez and Cavanagh (2004) are consistent with our data. That is, in

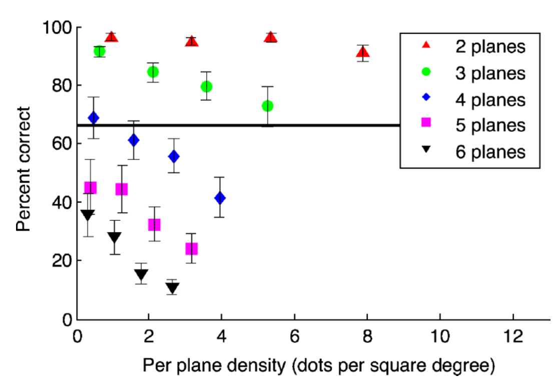

Figure 9. Data (shown in Figure 5) re-plotted as a function of per-plane density. Percent correct is plotted on the ordinate and per-plane density is on the abscissa. Differently colored data points correspond to different numbers of planes. Each data point represents performance averaged over subjects and disparity, for stimuli with a particular number of planes and overall density. The horizontal black line indicates threshold performance (see Results section for details).

more complex configurations (large densities and small disparities), only up to three planes could be detected. As the complexity of the stimuli decreased, observers could perceive up to six planes simultaneously. The smaller limit found by Greenwood and Edwards (2006) for motion transparency could be due to the particular stimulus configurations used. They did not manipulate the parameters of their stimuli, such as the number of moving dots and the depth difference between the planes; therefore, it is possible that the limit of three found in their experiment was a local limit defined by their stimulus configuration. The exact role of higher-level processes in perception of transparency is unclear and is a subject for further investigation.

Density and disparity

Our data show that increasing the density from modest levels impaired segregation at a given inter-plane disparity. We also found that segregation was impaired at small inter-plane disparities and improved with initial increases in depth separation between planes. The smallest inter-plane disparity 1.9′ falls well within the range of disparities (up to 3′–6′) reported for disparity pooling (Parker & Yang, 1989; Stevenson, Cormack, & Schor, 1991). When disparity pooling occurred, observers were unable to segregate the transparent planes and instead perceived a single plane or a thickened volume. As inter-plane disparity increased, disparity pooling weakened and segregation became easier for the subjects. However, for some stimuli, performance dropped again as inter-plane disparity increased beyond the peak disparity.

In agreement with our results, Akerstrom and Todd (1988) found that segregation of transparent surfaces became harder with large densities and disparities. No disparity pooling was observed in their study because the smallest disparity used was 7 min of arc. Akerstrom and Todd attributed the deterioration of the transparency percept with increases in density and disparity to a hypothetical competitive–cooperative network of interneural connections, where similarly tuned disparity detectors facilitate each other over a large neighborhood and detectors tuned to different disparities inhibit each other over smaller neighborhoods.

Gepshtein and Cooperman (1998) replicated the results of Akerstrom and Todd (1988) and proposed a model of long-range inhibitory connections to account for the phenomena. According to their model, an active disparity detector inhibits other detectors falling within a cone-shaped inhibitory zone defined by the disparity gradient limit (Burt & Julesz, 1980). With increases in disparity, the width and the overlap of the inhibitory zones also increase. Consequently, as disparity grows, more detectors fall in the overlapping regions of several inhibitory zones and are suppressed. They argued that as the density of the stimulus surfaces increases, the elements constituting the surfaces move closer activating adjacent disparity detectors. The inhibitory zones of neighboring detectors overlap more than these of distant detectors inflicting stronger inhibitory influence on other detectors.

While these long-range inhibitory connections can account for the results of Gepshtein and Cooperman (1998), they are not necessary. Instead, the observed detrimental influence of increases in disparity and density on stereo-transparency perception could simply result from the local receptive field properties of disparity detectors as described by an energy model (Anzai, Ohzawa, & Freeman, 1997; Cumming & DeAngelis, 2001; DeAngelis, Ohzawa, & Freeman, 1995; Prince, Cumming, & Parker, 2002; Prince, Pointon, Cumming, & Parker, 2002). According to this model, simple binocular cells compute the sum of the left and the right images filtered with the respective receptive fields (RFs). The RFs of these cells are described by Gabor functions such that each cell has a preferred spatial frequency. Disparity is encoded by a phase difference between the RFs in the two retinas, and consequently the range of disparities a cell can encode is bounded by its preferred spatial frequency. This property of disparity detectors, named the size-disparity correlation in the psychophysical literature (Prince & Eagle, 1999; Smallman & MacLeod, 1994; Tyler, 1975), can account for the effects of increases in both disparity and density. Fine scale disparity detectors have small receptive fields and hence can resolve high spatial-frequency details but cannot signal large disparities. Coarse scale detectors, on the other hand, have large receptive fields that can signal large disparities and resolve low frequency spatial variations. When the density of elements in the stimulus increases, they move closer together such that more elements fall on the receptive field of the same disparity detector (more so for coarser detectors). In pseudo-transparent stimuli, neighboring elements belong to different surfaces; hence, as density increases, the probability of elements with different disparities falling on the same receptive field grows. This degrades disparity estimates for individual elements and consequently hinders resolution of transparent stimuli. In other words, increasing density causes an increase in matching noise. As the disparity between overlaid surfaces is increased the visual system relies more and more on coarse scale detectors capable of encoding larger disparities. However, coarse scale detectors have large receptive fields and several elements in the stimulus can fall on the same coarse receptive field. The ability of a correlational disparity detector (such as the energy model) to resolve spatial detail is limited by its receptive field size (Banks, Gepshtein, & Landy, 2004). As a result, the detector averages the disparity signals for the elements, and the percept of transparency is degraded. We have simulated disparity energy cell responses at a range of scales and disparities and confirmed that selectivity of the disparity signal decreases with increased density in transparent stimuli.

It is important to note that one implication of the size-disparity correlation is that larger disparity values can be detected in sparser pseudo-transparent stimuli than in denser stimuli. This interaction of density and disparity is obvious in our data; the peak disparity beyond which increases in disparity degrades the transparency percept is a function of element density.

The interaction of disparity and density can account for the apparent inconsistency between the results reported by Wallace and Mamassian (2004) and the earlier literature. In contrast with present study, and the data reported by Akerstrom and Todd (1988), Wallace and Mamassian found no effect of increasing disparity on transparent surface segregation. However, Akerstrom and Todd used stimuli with a fixed density of 28.7 dots/deg^2 (we assumed that the dot size in their study was 1 pixel) and a maximum disparity of 112′, while Wallace and Mamassian used stimuli with a fixed density of 8.9 dots/deg^2 and a maximum disparity of 63′.

Our data suggest that the larger density and disparity used by Akerstrom and Todd (1988) likely placed the stimuli beyond the peak disparity. In contrast, the low density small disparity combination used by Wallace and Mamassian (2004) would likely have placed the stimuli prior to the peak disparity and consequently the detrimental effect of increasing disparity was not observed.

Gepshtein and Cooperman (1998) reported that the limiting density of a transparent plane, beyond which it is impossible to discriminate the orientation of a cylinder positioned behind the plane, decreased as the depth between the surfaces increased. Their data showed that the limiting density for disparity of 55′ is approximately 18.75 dots/deg^2 for one observer and 50 dots/deg^2 for another (these data were estimated from the graphs on page 2919). As suggested by Gepshtein and Cooperman's data, Wallace and Mamassian's (2004) stimuli were well within the upper performance limit imposed by density. However, Akerstrom and Todd's (1988) stimuli likely exceeded, this critical density so their results show the expected drop in performance with high disparities.

Conclusions

The perception of depth from pseudo-transparent stereoscopic stimuli represents a complex interaction between a number of stimulus parameters. Here we have shown that one important consideration is the fact that there is an optimal disparity for a given density and number of planes. Further, we suggest that this relationship does not simply reflect the total range of disparities present in the stimulus. We have also demonstrated that the degradation of the transparency percept with increasing density or inter-plane disparity beyond its peak value is consistent with theories of stereopsis, which incorporate a size-disparity correlation.

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Corresponding author: Robert S. Allison.
Email: allison@cse.yorku.ca.
Address: Center for Vision Research, York University, Toronto, ON, Canada.

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