The Impact of Object-Based Grouping on Perceived Depth Magnitude

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ABSTRACT

The amount of depth perceived between two vertical lines is markedly reduced when those lines are connected. Previously, this effect has been shown to be related to perceptual grouping of elements to form an object. The aim of the experiments reported here is to evaluate the generalizability of this phenomenon, to better understand its role in perception of depth from disparity in natural stimuli. I found that depth estimates were not affected by configuration over a range of suprathreshold disparities, in the presence of additional, reliable cues to depth. Taken together, these results show that previously reported reduction in perceived depth from perceptual grouping is restricted to specific viewing conditions and stimuli. Moreover, the effect is modulated by several factors including the presence or absence of orientation disparity, and the availability and consistency of other depth cues.

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INTRODUCTION

Defining stereopsis

Stereopsis refers to the perception of depth from retinal disparity that is a consequence of having eyes that are horizontally separated in the head. This results in two images that are offset relative to each other on the left and right retinas. The positional difference between the two-dimensional retinal images is called binocular disparity and this information is used by the brain to compute an estimate of the three-dimensional structure of the object or scene, relative to fixation (Wheatstone, 1838; Marr, 1982). Even in the absence of other depth cues, stereopsis provides a powerful, vivid percept of depth (Wheatstone, 1838; Howard & Rogers, 2012). Stereoacuity is a measure of the smallest depth difference that can be reliably detected from binocular disparity. The visual system is able to discriminate relative disparity with remarkable precision. Under ideal conditions, discrimination thresholds for practiced observers can be as low as 2-6 seconds of arc; but tend to be higher in the general population (Ogle, 1952; Blakemore, 1970; Westheimer, 1979; Westheimer & McKee, 1979; Badcock & Schor, 1985; Coutant & Westheimer, 1993). Researchers have shown that the lowest thresholds are obtained using stimuli with high contrast, sharp edges viewed approximately at arm's length (Johnston, 1991; Volcic et al., 2013). Low-level stimulus attributes that have been shown to influence stereoacuity include spatial frequency, depth modulation frequency, luminance, and exposure duration (Ogle & Weil, 1958; Schor & Wood, 1983; Schor, Wood, & Ogwa, 1984; Christopher & Rogers, 1994; Howard & Rogers, 1995; Siderov & Harwerth, 1995). These attributes are referred to as low-level properties as they involve the representation of elementary features that are linked to early processing in the primary visual cortex (V1) (Cumming & Parker, 1997; Welchman et al., 2005; Groen, Silson, & Baker, 2017).

In addition to providing a precise measure of the minimal detectable disparity signal, the stereoscopic system also provides information regarding the magnitude of depth, or the amount of depth present between two elements. It is important to understand suprathreshold depth percepts, as the majority of our everyday visual tasks depend on judging depth differences between objects whose separation is well above discrimination threshold (e.g. avoiding obstacles, reaching, and grasping objects). There is evidence that suprathreshold depth estimation is also influenced by low-level stimulus attributes. However, the impact of these factors is not necessarily the same at and above threshold (Richards & Foley, 1974; Schor & Howarth, 1986; Patel, Bedell, & Tsang, 2009; Bedell, Gantz, & Jackson, 2012). For example, Bedell, Gantz, & Jackson (2012) showed that simple image manipulations that elevated thresholds (glare and luminance) did not reduce perceived depth of the same targets presented at larger disparities. Similarly, Patel, Bedell, & Tsang (2009) showed that increasing the gap between targets and introducing stimulus blur substantially elevated thresholds, while suprathreshold depth remained unchanged. Furthermore, research has consistently shown that estimates of suprathreshold depth do not necessarily match theoretical, geometric predictions (Schor & Howarth, 1986; Bülthoff, Fahle, & Wegmann, 1991; Johnston, Cumming & Parker, 1993). Some factors that are known to contribute to distortions in perceived depth include the presence of cue conflict with monocular depth cues, mis-estimation of viewing distance (Volcic et al., 2013), and the observers' level of experience with psychophysical tasks (McKee & Taylor, 2010; Hartle & Wilcox, 2016).

Configural effects

As mentioned above, stereopsis is known to be dependent on low-level stimulus attributes such as spatial frequency and luminance. However, stereoscopic discrimination thresholds are also influenced by mid-level stimulus attributes, such as configuration (Werner, 1937; Westheimer, 1979; McKee, 1983; Mitchison & Westheimer, 1984; Zalevski, Henning, & Hill, 2007). For instance, McKee (1983) used two vertical line targets displaced in depth and systematically varied the horizontal connection between them. She showed that discrimination thresholds were lowest when the two vertical lines were shown in isolation, but increased significantly when the lines were connected by two horizontal lines to form a rectangle. The disparity signal was identical in all conditions, yet thresholds for the vertical line pair consistently increased when they were connected. Mitchison & Westheimer (1984) found similar effects on disparity thresholds when varying connectedness between two identical vertical lines. Thresholds were lowest for a pair of isolated lines and increased when the lines were connected to form a square. Thresholds fell somewhere in between these two conditions depending on the degree to which the pair of lines were connected. Figure 1 is a reproduction of the stimuli and some of the results reported by Mitchison & Westheimer (1984). They found that the presence of any connection between the vertical lines was sufficient to degrade sensitivity; thresholds were highest for the square configuration, and remained substantially elevated when the central parts of the horizontal lines were removed to create two brackets slanted in depth (Mitchison & Westheimer, 1984). In a subsequent study, Fahle & Westheimer (1988) showed that depth discrimination thresholds for a pair of dots significantly increased when one dot was added between the target pair. Moreover, the systematic

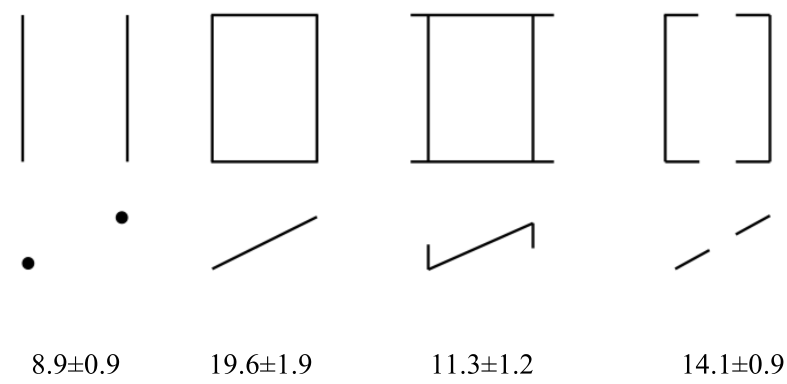


Figure 1. Stimulus configurations used by Mitchison and Westheimer (1984). The top row shows how they appeared on the screen, and the bottom row shows a view from above, to illustrate the configurations in depth. The vertical lines are displaced in depth to measure thresholds, and are identical in all conditions. Corresponding disparity thresholds for each figure are listed underneath the configurations.

addition of dots increased thresholds further (Fahle & Westheimer, 1988). A number of explanations have been proposed to account for the elevation of thresholds reported by these authors. Examples of these include, cue conflict arising from the inconsistencies between disparity and perspectives cues (Zalevski, Henning, & Hill, 2007), disparity pooling or averaging (McKee, 1983; Fahle & Westheirmer, 1988), saliency (Mitchison & Westheimer, 1984), and the influence of a fronto-parallel reference plane (Mitchison & Westheimer, 1984; Fahle & Westheimer, 1988; Glennerster & McKee, 1999). Although mid-level processes such as perceptual grouping have been referred to as a potential cause of degraded depth effects in these configurations, this explanation was not directly evaluated until the recent work of Deas & Wilcox (2014; 2015). These authors used a suprathreshold depth estimation paradigm, and systematically evaluated the impact of 2-D and 3-D perceptual grouping. They proposed that top-down, 2D Gestalt grouping principles (closure and good continuation) leads to object-based disparity smoothing which in turn results in reduced relative depth percepts (Deas & Wilcox, 2014).

Perceptual grouping and distortions in perceived depth

It is widely believed that the visual system interprets objects using a set of principles that govern perceptual organization (Wertheimer, 1923; Koffka, 1935; Palmer, 1992; Wagemans et al., 2012). As proposed by the Gestalt psychologists, these principles include closure, good continuation, common fate, simplicity, similarity, and proximity (Wertheimer, 1923). Closure is a well-studied Gestalt principle of perceptual organization, and is particularly important in object perception. It posits that elements that form a closed figure tend to be grouped together (Wertheimer, 1923; Koffka, 1935; Todorovic, 2008). Deas and Wilcox (2014) used a modified version of McKee's (1983)

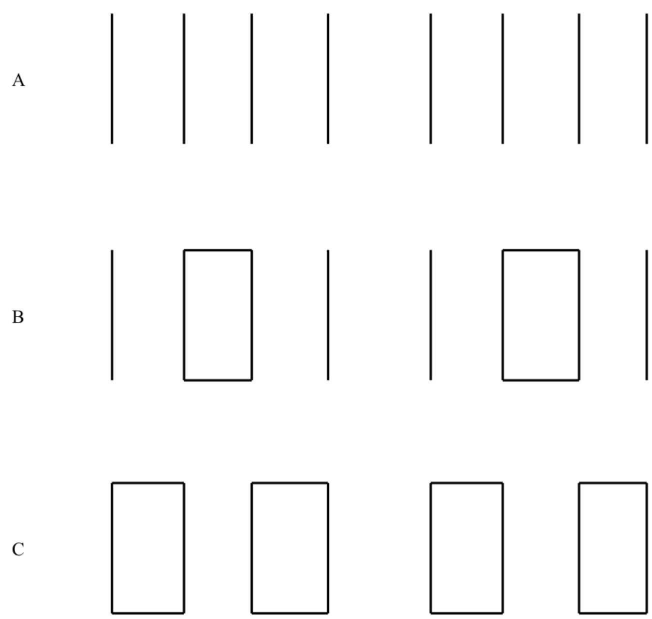


Figure 2. Sample stereograms used by Deas and Wilcox (2014) illustrate the stimulus. By crossing the eyes to fuse the outer vertical lines in each pair one can appreciate the depth offset in the central line pair. The vertical lines are identical in all 3 configurations. Observers estimated the depth between the two central vertical lines in each condition. Thresholds are significantly larger for configuration B than for A and C (Deas & Wilcox, 2014).

stimulus configuration and directly assessed the impact of perceptual grouping by closure on perceived depth magnitude (Figure 2). They manipulated stimulus properties that influenced perceived closure, and measured both the degree to which the observers perceived closure and the amount of depth that was perceived. They found that there was a significant reduction in depth magnitude reported when closure was perceived between the target elements. Since perceived closure was closely correlated with a reduction in perceived depth magnitude, Deas and Wilcox (2015) argued that other grouping cues might also potentially lead to reductions in depth percepts. Echoing the results of Fahle & Westheimer (1988), Deas and Wilcox (2015) showed that the suprathreshold percept of depth between two target dots is systematically degraded by both the addition of dots between the targets and the presence of a smooth disparity gradient. Systematic manipulations of the stimulus revealed that, in this case, the reduction in perceived depth from disparity resulted from grouping via 3D-good disparity continuation (Deas & Wilcox 2014; 2015). Deas and Wilcox (2014; 2015) argue that the dependence of the reduced depth percepts on perceptual grouping shows that high-level operations impact low-level depth discrimination. A compelling example of the impact of grouping on perceived depth in their 2014 publication is shown in Figure 3. In this case, they added flanking lines alongside the horizontal connectors in the closed object condition. When the flanking lines and connectors had the same contrast polarity as the target lines, perceived depth was greatly reduced. However, reversing the polarity of the connectors and flankers (relative to the target lines) eliminated the degraded depth effect (Deas & Wilcox, 2014).

One implication of this argument is that as long as grouping via closure and good continuation is present, perceived depth should be reduced; changes to the position or orientation of the configuration should not impact performance. In the experiments

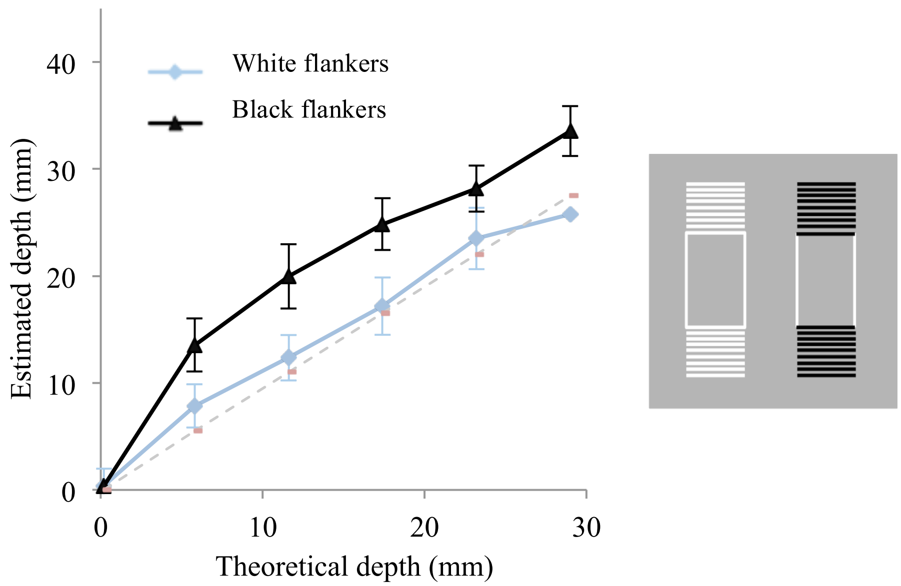


Figure 3 A reproduction of the results obtained by Deas and Wilcox (2014). Estimated depth (mm) is plotted as a function of theoretical depth (mm) for two stimulus configurations: White Flankers (circles), Black Flankers (squares). The target lines were vertical and there was a change in disparity along the horizontal axis. The dotted line represents the geometrically predicted depth at each disparity. Error bars represent ± one standard error of the mean.

reported here I test this prediction. In Experiment 1 I replicate and extend the experiments performed by Deas and Wilcox (2014). Subsequently, using the same stimuli and observers, I evaluate whether the disruptive effects of grouping are seen when the stimuli are rotated 90° so they contain vertical gradients of horizontal disparity. In Experiment 2, I assess the impact of grouping on the precision of depth estimates in these line stimuli. Next, in Experiment 3, I evaluate the role of the direction of the disparity gradient and the subsequent change in disparity present along the contour. In Experiment 4, I evaluate the role of cue conflict between disparity and linear perspective in the reduction of depth estimates. Finally, in Experiment 5, I further assess the relationship between stereopsis and grouping using physical stimuli to investigate whether the same distortions in perceived depth are apparent in the presence of multiple, consistent 2D depth cues.

GENERAL METHODS

Observers

A total of thirty-two observers were recruited and a subset of these observers participated in each of the experiments described here. Twenty-seven were inexperienced, and had no prior experience with psychophysical experiments. These observers were either lab members, or recruited through the York University Undergraduate Research Participant Pool (URPP). Five were practiced stereoscopic observers with previous experience completing psychophysical tasks. All of the participants had normal to corrected-to-normal vision, and their stereoacuity was tested prior to participation in the experiments using the RANDOT™ test. An exclusion criterion was applied, and participants had to have a threshold of at least 40 seconds of arc. Observers were also assessed to ensure that they could reliably perform a depth magnitude estimation task. Each observer's interocular distance (IOD) was measured using a ruler; the average IOD was 60mm, and ranged from 56mm to 62mm. The research protocol used here and in all subsequent experiments was approved by the York University research ethics board.

Apparatus

For all experiments that used computer-generated stimuli (1-4) the stimuli were created using the Psychtoolbox (Brainard, 1997; Pelli, 1997) package for Matlab™ on a Mac OS X computer. The stereopairs were displayed on two calibrated LCD Dell monitors in a mirror stereoscope arrangement. The monitor resolution was 1920 x 1200 pixels, with a refresh rate of 75 Hz. During testing, the seated observer faced the mirrors, which were positioned at 90˚; the viewing distance was 74cm. The monitors were calibrated prior to testing and a chin rest was used to stabilize the observers' head position.

Procedure: Depth magnitude estimation

A depth magnitude estimation task was used for all experiments, except for Experiment 2. Depth estimates were made using a purpose-built, touch sensitive sensor (Figure 4). The haptic sensor consisted of a rectilinear SoftPot membrane potentiometer mounted on a thin aluminum bar. The sensor strip was 200mm x 7mm, was connected to an analog to digital converter and a 16-bit micro controller. A Matlab script was used to convert the voltage to millimeters. Linear measurements were made along the 200mm length, with a resolution of approximately 0.2mm. During testing, the observer positioned their thumb at the base of the sensor resting against an adjustable rod. The rod was positioned for each observer prior to testing to take into account differences in thumb thickness. On each trial they were asked to indicate the amount of depth they perceived (between two regions of the stimulus) by pressing the side of their index finger at some point along the sensor strip. A small red LED positioned in front of the stereoscope

A

B

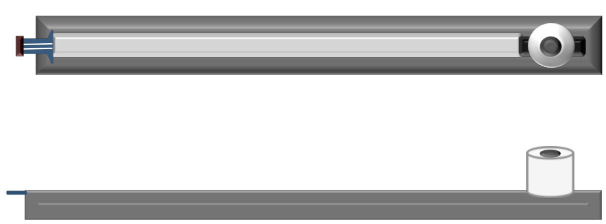


Figure 4 (A) A top down view, and (B) a side view representation of the haptic sensor used for the depth magnitude estimation task.

mirrors, and 10.8° below the line of sight to the stimulus, were illuminated when sufficient pressure was applied to the sensor strip. The LED was extinguished when no pressure was applied to the strip. When satisfied with their estimates, observers pressed the spacebar to record the response and move on to the next trial. Between trials, observers were told to reposition their index finger at the base of the sensor. Prior to testing, observers completed a brief practice session of 60 trials to familiarize them with the depth estimation technique.

The haptic sensor used here has been validated in a separate study by Hartle & Wilcox (2016), in which observers were asked to estimate the depth between a pair of vertical lines using a haptic sensor, a digital caliper that manually measured digit span estimates, and a visual virtual ruler displayed on the computer screen with an adjustable cursor (Hartle & Wilcox, 2016). Hartle and Wilcox showed that with some practice observers can consistently and accurately estimate relative depth using this technique. Critically, irrespective of experience they found that the three depth estimation techniques produced remarkably consistent results (Hartle & Wilcox, 2016).

Theoretical depth from disparity

Stimulus disparities were converted to theoretical depth in each experiment to simplify comparison of predicted and reported depth percepts. The formula that relates disparity to predicted depth at a known viewing distance (74cm) was used: Predicted Depth $\cong$ $((d*\pi/180)*D^2/IOD)$, where d is the relative disparity in degrees, D is the viewing distance, and IOD is the inter-ocular distance (Howard & Rogers, 2012). The average inter-ocular distance of the observers that participated in a particular experiment were used to convert disparity depth for Experiment 1, Experiment 3, and Experiment 5. For Experiment 4, the Individuals' IOD was used in order to calculate depth from disparity, and to calculate the corresponding perspective projection.

EXPERIMENT 1

Introduction

As outlined in the introduction, a number of studies have shown that perceived depth is degraded as a result of stimulus configuration in which a pair of vertical lines are connected by horizontal ones to form a uniform closed object (McKee, 1983; Mitchison & Westheimer, 1984; Deas & Wilcox, 2014). Perceptual grouping has been proposed to mediate this reduction in perceived depth (Deas & Wilcox, 2014; 2015). The aim of Experiment 1 was to investigate whether reduced depth estimates are a general consequence of Gestalt grouping by closure, more specifically, if they apply to a grouped surface regardless of whether the surface is slanted with a horizontal or vertical gradient of disparity. To do this, I replicated the results obtained by Deas and Wilcox (2014), who used an adaptation of the stimuli used by McKee (1983). Additionally, using the same stimuli and observers, I evaluated whether the disruptive effects of grouping are seen when the stimuli are rotated 90˚. In addition to measuring perceived depth, I also asked observers to provide subjective ratings of closure for each of the stimulus configurations. These data permit comparison between depth estimates and quantitative measures of perceived closure.

Observers

Eighteen observers participated in Experiment 1. Thirteen of these students had no experience with stereoscopic, psychophysical tasks. The remaining five participants were experienced with stereoscopic tasks, and had prior experience with psychophysical experiments.

Stimuli

The stimuli comprised four white lines (59.1 cd/m^2) displayed on a mid-grey background (15.6 cd/m^2) positioned symmetrically about the mid-point of the display. Each line measured 3.30˚ x 0.1˚, and was separated from the neighbouring line by 2.10˚. Three configurations were created for each orientation (vertical and horizontal axis) for a total of six test configurations (Figures 5.1 and Figure 5.2).

A. Isolated Lines: Four lines were presented in isolation, observers judged the relative depth of the central target pair.
B. Single Closed Object (Within Object): The central line pair was connected at corresponding endpoints to form a rectangle. The target lines were the same as in A, but now they formed the edges of a single closed rectangle.
C. Two Closed Objects (Between Object): The two outer line pairs were connected at the endpoints to create two rectangles. The central target lines formed the vertical edges of two discrete objects.

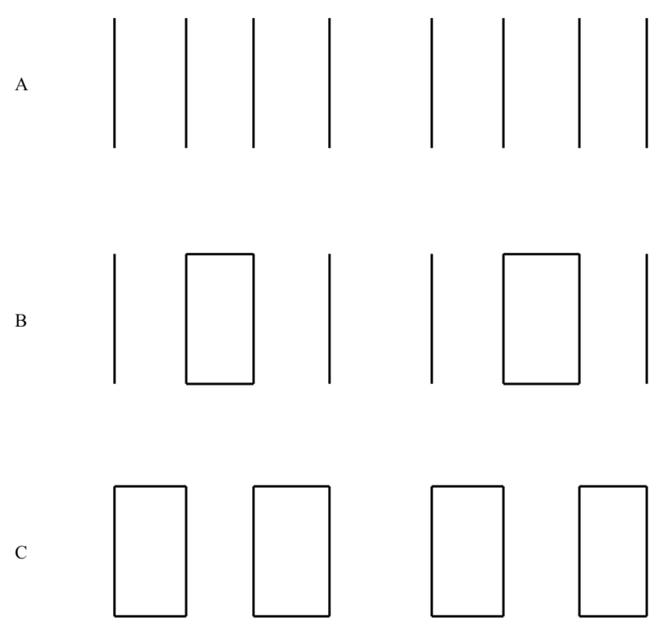


Figure 5.1. Sample stereograms used in Experiment 1. The two central target lines are vertical and there is a horizontal gradient of disparity between them. By crossing the eyes to fuse the outer pair of lines in each configuration one can appreciate the depth offset in the central line pair. In each of these stereograms, the rightmost line of the central line pair has the same crossed disparity. The vertical lines are identical in all 3 configurations. Each row depicts one condition (A) Isolated Lines (B) Closed Object (C) Two Closed Objects.

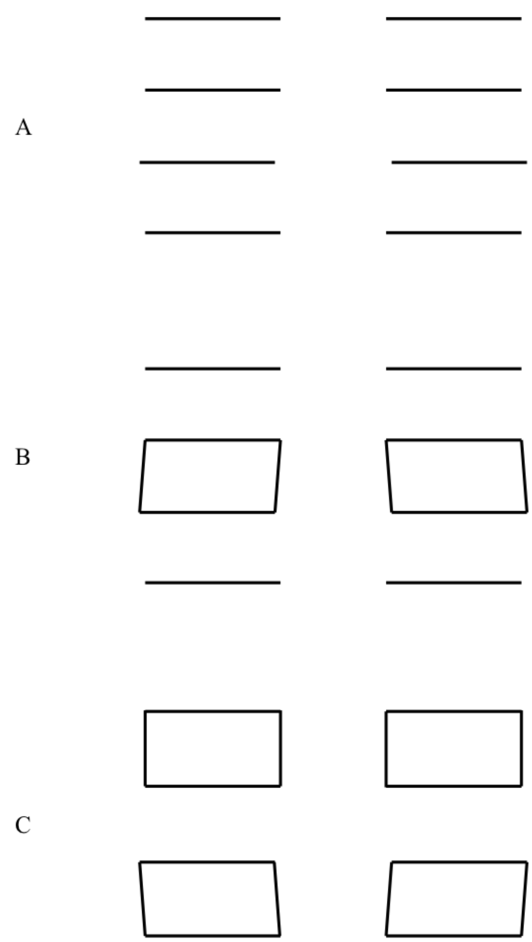


Figure 5.2. Sample stereograms used in Experiment 1. The two central target lines are horizontal and there is a vertical gradient of horizontal disparity between them. By crossing the eyes to fuse the outer pair of lines in each configuration one can appreciate the depth offset in the central line pair. In each of these stereograms, the bottommost line of the central line pair has the same crossed disparity. The horizontal lines are identical in all 3 configurations. Each row depicts one condition: (A) Isolated Lines (B) Closed Object (C) Two Closed Objects.

The stereopair was centred at the midpoint of the display. The closed objects subtended 3.30˚ x 2.20˚, and the connecting lines had the same width (0.1˚) and luminance (59.1 cd/m^2) as the other lines. When the lines were connected to form closed objects, they looked like slanted planar surfaces rotated either around the vertical axis with a horizontal disparity gradient, or around the horizontal axis with a vertical disparity gradient.

On each trial, one line of the central pair was displaced by one of a range of crossed disparities (0.00˚, 0.05˚, 0.10˚, 0.15˚, 0.20˚, and 0.25˚) while the other three lines were fixed at zero disparity. This range was selected to avoid diplopia, and generated suprathreshold predicted depth percepts of approximately 0, 8, 16, 24, 32, and 40 mm.

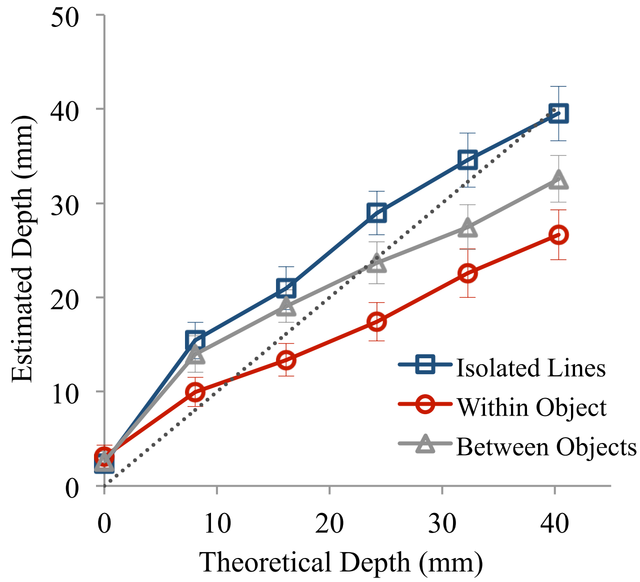
Procedure

Depth Magnitude At the beginning of each trial, a white (59.1 cd/m^2) fixation cross (1.5˚ x 1.5˚) was presented at the center of the screen for 750ms. On each trial, one of the two central target lines, randomly selected on each trial, was presented at one of the six test disparities. For all configurations, observers were asked to judge the amount of depth between the central pair of lines. Observers used the haptic sensor strip (described in the General Methods section) to record their depth estimates. Prior to testing, observers were told that some stimuli would have zero disparity. In previous experiments with this device it was noted that observers occasionally found it difficult to indicate that there was no depth versus a small amount of depth. To eliminate this potential source of error observers were instructed to place their index finger at the far end of the sensor strip when they saw no depth. The stimulus remained on the screen from the beginning of the trial until the observer recorded their response by pressing the spacebar, which then initiated the onset of the next trial. This experiment was divided into two blocks, one for each orientation, which was completed in pseudo-random order (half of the observers started with the horizontal disparity gradient stimuli, while the other half of the observers started with the vertical disparity gradient stimuli). Each block took approximately 15 minutes to complete, and a break was provided between the two sessions. Both the blocks were completed in one sitting. Each block consisted of 18 conditions (6 disparities x 3 configurations), with each condition presented 10 times in random order (either one of the central lines in depth), for a total of 180 trials per block.

Subjective ratings All eighteen participants returned after testing to complete a subjective ratings task in which they were asked to evaluate the extent to which the central line pair appeared to be part of a single object. The ratings ranged from 0 = not an object, to 10 = a distinct object. The 6 stimulus configurations were displayed on the stereoscope in random order at the largest (0.25˚) smallest (0.00˚) test disparity. Each condition-disparity combination was repeated 4 times, for a total of 48 trials.

Results and Discussion

The mean estimated depth for each condition as a function of predicted depth is plotted in Figure 6 a,b. In all six conditions, as the disparity between the central line pair increased, estimated depth increased. The results in the isolated line conditions are similar for the two orientations, and show depth is overestimated at all but the extreme disparities. The overestimation seen in Figure 6 a,b is consistent with previous studies that have shown that the perception of depth based on stereopsis is overestimated at relatively short viewing distances (<80cm) (Foley, 1980; Johnston, 1991). In their study, Hartle & Wilcox (2016) reported similar overestimates using these line stimuli at the viewing distance and disparity range tested here. Figure 6a shows that, as reported by Deas and a.



b.

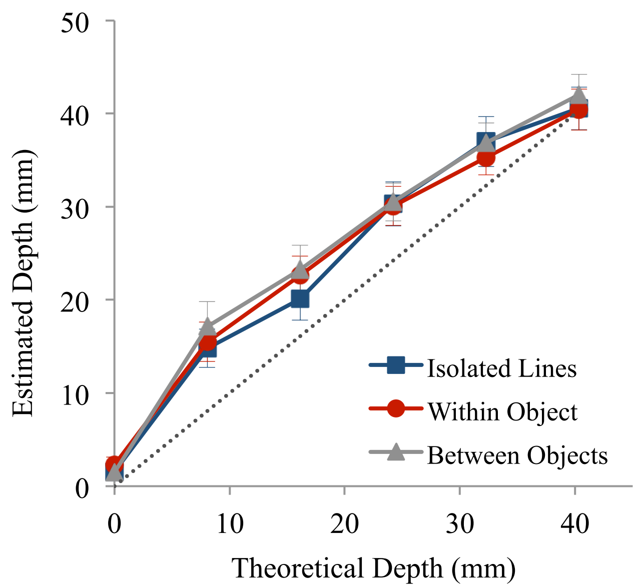


Figure 6. Estimated depth (mm) is plotted as a function of theoretical depth (in mm) for the three stimulus configurations: Isolated Lines (squares), Single Closed Object (circles), and Two Closed Objects (triangles) for both orientations (a.) The target lines are vertical and there is a horizontal gradient of disparity. (b.) The target lines are horizontal and there is a vertical gradient of horizontal disparity. The dotted black line represents the geometrically predicted depth at each disparity. Error bars represent ± one standard error of the mean.

Wilcox (2014), when vertical target lines were connected by horizontal lines to form a closed object, the amount of depth perceived between the central vertical lines was consistently degraded compared to the isolated lines condition. In this study, when the targets formed the boundaries of separate objects, depth estimates fell between the isolated lines and single closed object conditions. This result is inconsistent with Deas and Wilcox (2014), who found similar depth estimates in the closed object and isolated lines conditions. Interestingly, a different pattern of results was seen when the target lines were horizontal and the stimuli had a vertical gradient of horizontal disparity (Figure 6b). In this case, perceived depth was similar across conditions, and estimates were close to theoretically predicted values.

These observations were confirmed statistically using a repeated measures analysis of variance. Mauchly's test of sphericity showed that the assumption of sphericity was violated for the interaction between Direction of the Disparity Gradient x Stimulus Configuration x Disparity, so the Greenhouse-Geisser correction was applied. There was a significant three-way interaction between Direction of the Disparity Gradient x Stimulus Configuration x Disparity, $F(4.70, 79.98) = 5.78$, $p<0.0001$; $\eta^2 = 0.25$). That is, the effect of stimulus configuration as a function of disparity was dependent on the direction of the disparity gradient.

To further explore the three-way interaction between the Direction of the Disparity Gradient x Stimulus Configuration x Disparity the results were subdivided into two groups based on the direction of the disparity gradient. Differences between the stimulus configurations as a function of the direction of the disparity gradient (vertical or horizontal) are discussed below.

Horizontal Disparity Gradient For the vertical target lines that had a horizontal gradient of disparity (Figure 6a), a repeated measures analysis of variance showed that there was a significant main effect of Stimulus Configuration, $F(2,34) = 34.48$, $p<0.0001$; $\eta^2 = 0.67$, Disparity, $F(1.74, 29.66) = 103.54$, $p <000.1$, $\eta^2 = 0.86$, and a significant interaction between Stimulus Configuration x Disparity, $F(4.99, 84.82) = 9.95$, $p<0.0001$, $\eta^2 = 0.37$. Given that Mauchly's test of sphericity was violated for the main effect of Disparity and the interaction of Stimulus Configuration x Disparity, the Greenhouse-Geisser correction was applied. To further investigate the differences between the three stimulus configurations, I used pairwise t-tests and Benjamini-Hochberg's (1995) (BH procedure) method for controlling false discovery rates. The interaction between stimulus configuration and disparity was primarily driven by significant differences between the isolated lines and single closed object condition ($p<0.001$) and between the single closed object and two closed objects condition ($p<0.01$) at every disparity level, except at zero disparity. There were also significant pair-wise differences between the isolated lines and two closed object conditions at the three largest disparities with $p=0.001$, $p=0.002$, and $p=0.004$, respectively. As noted above, the reduction in the amount of depth perceived in the closed object condition compared to the isolated lines condition replicates Deas & Wilcox (2014). However, the results from the between object condition of this study differ from those of Deas & Wilcox (2014) who found that depth percepts in the between object condition were the same as those reported for the isolated lines. Since the stimuli and apparatus were the same in these studies, it is likely that the difference is due to differences between the two groups of observers.

Vertical Disparity Gradient A repeated measures analysis of variance showed that there was a significant main effect of Disparity, $F(2.04, 38.94) = 149.52$, $p<0.0001$, $\eta^2 = 0.90$)

in the horizontal lines, vertical gradient of disparity condition. However, there was no main effect of Stimulus Configuration, $F(2,34) = 2.11$, $p=0.14$, $\eta^2 = 0.11$) and no significant interaction between Stimulus Configuration x Disparity $F(4.58, 77.88) = 1.38$, $p=0.24$, $\eta^2 = 0.07$). Thus the analyses support the observation that the reduction in perceived depth attributed to grouping by Deas and Wilcox (2014), does not occur when estimating the depth between horizontal lines that form the edges of a closed object. It is possible that the absence of a grouping effect in the closed object condition that had a vertical gradient of horizontal disparity is due to a reduced sense of closure for these stimuli. However, subjective ratings (Figure 7) show that the interpretation of the stimulus as a closed object does not vary with the direction of the disparity gradient.

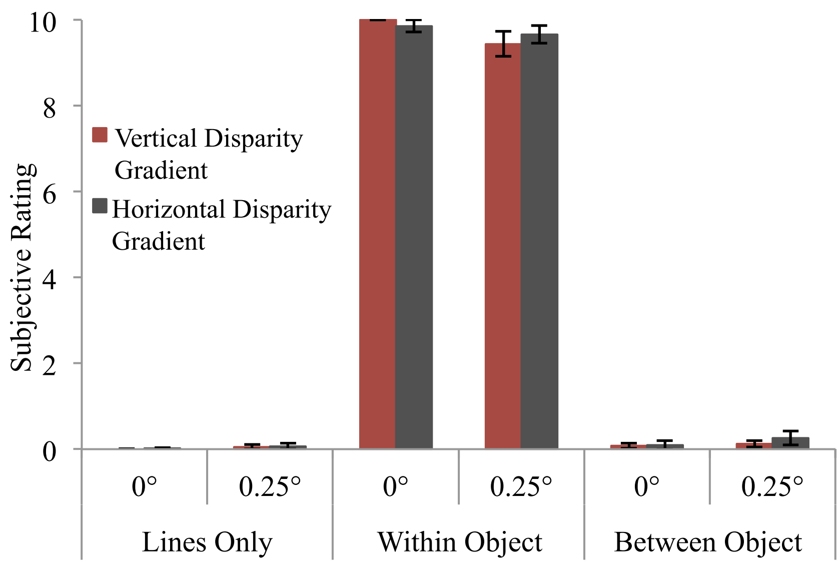


Figure 7. Average subjective ratings for the six stimulus configurations used in Experiment 1. Observers indicated whether the central target lines formed a single object. Ratings range from 0 (not an object) to 10 (a distinct object). Error bars represent ± one standard error of the mean.

In the isolated lines and two closed objects conditions, the two central target lines were seen as two distinct objects regardless of the orientation or disparity present within them;

ratings were always close to 0. In the single closed object condition, irrespective of the stimulus orientation, participants consistently reported that they perceived a strong sense of a closed object, with ratings consistently ≥ 9. From these results it is clear that the strength of the percept of the stimulus as a closed object is not responsible for the difference between the two conditions.

The aim of Experiment 1 was to assess the impact of figural closure on suprathreshold estimates of depth from disparity, and to determine if the previously reported reduction in perceived depth is influenced by the direction of the disparity gradient. Deas & Wilcox (2014) argued that the interpretation of the stimulus as a distinct object was primarily responsible for degraded depth precepts. If this were true, we would expect the phenomenon to occur regardless of the orientation of the slant of the grouped surface. However, when the closed object contained a vertical gradient of disparity, participants reported strikingly similar amounts of depth compared to the isolated lines condition. This suggests that the phenomenon observed by Deas and Wilcox (2014) and others (Westheimer, 1979; McKee, 1983; Mitchison & Westheimer, 1984; Fahle & Westheimer, 1988), is specific to stimuli within which the horizontal disparity varies along the horizontal axis. This conclusion is supported by comparison of magnitude estimates obtained in the two single closed object conditions. When the closed object was oriented so that disparity changed along the horizontal axis, perceived depth was significantly reduced between the vertical target lines; this reduction was eliminated when the closed object was oriented so that disparity changed along the vertical axis and depth estimates were made between the horizontal target lines. Critically, according to subjective ratings, a high degree of closure was perceived in both of the closed object configurations, regardless of their orientation.

These results were obtained using a specific depth magnitude estimation task. It is possible that the impact of the direction of the disparity gradient on perceived depth was somehow related to the depth estimation task used in the study. To evaluate this possibility, in Experiment 2 I used the same stimuli and assessed the impact of grouping and orientation on observers' ability to discriminate between these suprathreshold depth offsets.

EXPERIMENT 2

Introduction

In Experiment 1, I used a depth magnitude estimation paradigm and found that the reduction in perceived suprathreshold depth was contingent on perceptual grouping of elements to form an object, but only in the presence of a horizontal gradient of disparity. To assess whether these results were related to the estimation method, in this experiment I used a forced choice, depth discrimination task with the same line stimuli. If the impact of disparity gradient in Experiment 1 reflects a fundamental property of disparity processing, then this pattern of results should also be evident when observers are asked to discriminate between two suprathreshold stimuli.

Observers

Eleven observers participated in Experiment 2. Eight of these students were relatively inexperienced; the other three observers were highly experienced with psychophysical experiments using stereoscopic stimuli.

Stimuli

The stimuli were identical to those described in Experiment 1. Three stimulus configurations: Isolated Lines, Single Closed Object, and Two Closed Objects were shown at two orientations (see Figures 5.1 and 5.2).

Procedure

Depth Discrimination A two-interval forced-choice (2IFC) method of constant stimuli was used, with nine test disparities. On a given trial, the observer was presented with two intervals and was asked to indicate via button press which interval contained the stimulus with more depth. The observer initiated a trial by pressing a button on the gamepad and each trial began with the presentation of a white (59.1 cd/m^2) fixation cross (1.5˚ x 1.5˚) with zero disparity presented at the center of the screen for 750ms, followed by the stimulus. The first (reference) interval always contained the isolated lines configuration where one of the lines of the central pair was displaced at a fixed disparity of 0.16˚. The second (comparison) interval contained one of the three configurations; isolated lines, closed object, or two closed objects. In a given trial, the same line was displaced in depth in the two intervals. A step size of 0.04˚ was used, with four levels greater than and four levels less than the disparity of the reference stimulus (0.16˚). The second interval was presented at one of the test disparities (0.00˚, 0.04˚, 0.08˚, 0.12˚, 0.16˚, 0.20˚, 0.24˚, 0.28˚, 0.32˚). Each of the two intervals was presented for 400ms; the fixation cross was presented between the two intervals for 200ms. The experiment was split into two blocks in pseudo-random order; one for the vertical target lines with a horizontal disparity gradient, and one for the horizontal target lines with a vertical gradient of horizontal disparity. Each block consisted of 3 stimulus conditions and 9 test disparities repeated 20 times for a total of 540 (3 x 9 x 20) trials. A black rectangle was presented on the screen after trial numbers 180 and 360 to cue the observer to take a break.

Results and Discussion

The psychometric data obtained from every observer for each configuration was fit using a cumulative normal function. The point of subjective equality (PSE) was computed for each condition, for both orientations and all observers, using a MatLab script presented in Kingdom & Prins (2010). The PSE is the magnitude of a stimulus, which appears to be perceptually equivalent to a comparison stimulus. It is the position of the curve along the x-axis that corresponds to the 50% value of the proportion 'larger' (Kingdom & Prins, 2010). The analysis was performed in MatLab using the PAL_CumulativeNormal function in the Palamedes toolbox. The estimate of error was determined with a bootstrap analysis using the PAL_PFML_BootstrapParametric function that ran 400 times for each dataset. In this study, the reference was always presented in the first interval; a shift in the PSE represents the tendency to perceive the target as having more (right ward shift) or less depth than the reference.

A repeated measures analysis of variance was used to compare the effect of direction of the disparity gradient and stimulus configuration as a function of disparity. In terms of the PSE or bias, there was a significant interaction between the Direction of the Disparity Gradient x Stimulus Configuration, $F(2,20) = 6.10$, $p<0.01$, $\eta^2 = 0.38$. This indicated that there was a significant difference in perceived disparity between the three stimulus configurations, which depended on the direction of the disparity gradient. The data were subdivided based on the direction of the disparity gradient to further examine differences in depth discrimination between the three stimulus configurations. An independent analysis of variance was performed for each orientation. The differences in PSE in the three stimulus configurations for each orientation are discussed below.

Horizontal Disparity Gradient The mean PSE for the three test configurations containing a horizontal disparity gradient can be seen in Figure 8. For most of the observers, the point of subjective equality for the isolated lines condition was similar to the disparity of the reference (9.6 arcmin), while the PSE for the single closed object condition was much larger. PSEs for the two closed objects condition lie between those obtained for the isolated lines and single closed object conditions. A repeated measures analysis of variance showed a main effect of Stimulus Configuration, $F(2,20) = 11.88$, $p < 0.01$, $\eta^2 = 0.54$. Pairwise t-tests (using the BH procedure to control the false discovery rate) confirmed that the effect was driven by significant differences between the isolated lines and single closed object conditions ($p<0.01$) and between the single closed object and two closed objects conditions ($p = 0.01$), there was no significant difference between the isolated lines and two closed objects conditions. Importantly, as would be expected if observers performed the task appropriately the PSE for the isolated lines condition was

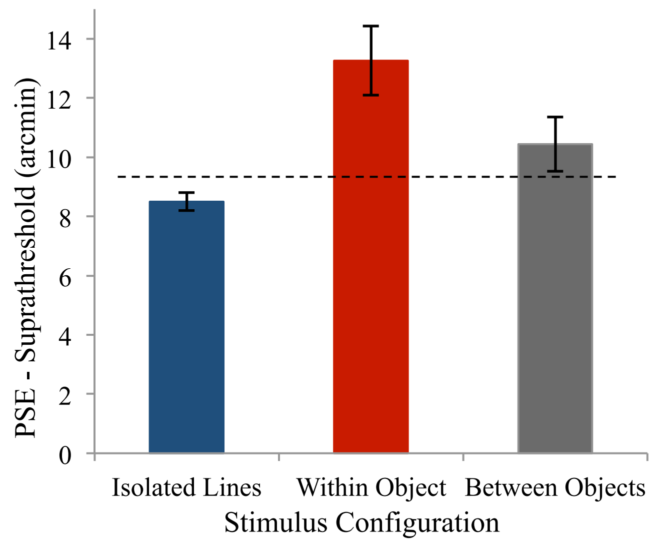


Figure 8. Average PSE for each of the three configurations: Isolated Lines (blue), Within Object (red), and Between Objects (grey) when the stimulus contained a horizontal gradient of disparity. The horizontal black dotted line represents the disparity of the reference. Error bars represent ± one standard error of the mean.

very similar to the disparity of the reference stimulus. In the single closed object condition (red) in Figure 8, it appears that significantly more depth was required between the central line pair for the closed object to be perceived as equivalent to the isolated lines condition. These results echo the result obtained by Deas and Wilcox (2014) and replicate Experiment 1. That is, irrespective of the task used, when the closed object has a horizontal disparity gradient, perceived depth between the vertical boundaries is reduced. The PSE obtained in the two closed objects condition (grey) was significantly larger than in the single closed object condition (p=0.01). This result replicates the between object results in Experiment 1 (see Figure 6a). It appears that even when the task was to judge the amount of depth between the edges of two separate objects, the depth within each of those individual rectangles is degraded.

Vertical Disparity Gradient The mean PSE for the three test configurations when the gradient of horizontal disparity is vertical can be seen in Figure 9. For the majority of the

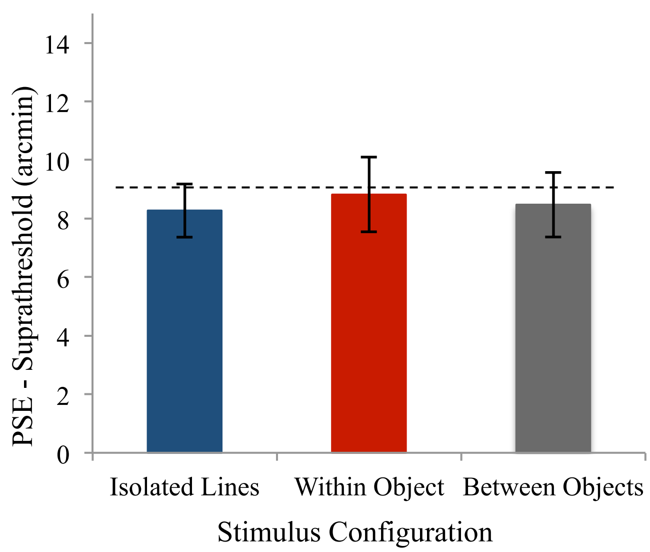


Figure 9. Average PSE for each of the three configurations: Isolated Lines (blue), Within Object (red), and Between Objects (grey), when the stimulus contained a vertical gradient of horizontal disparity. The horizontal black dotted line represents the disparity of the reference. Error bars represent ± one standard error of the mean.

observers, in all three conditions, the PSE was similar to the disparity of the reference (9.6arcmin). A repeated measures analysis of variance confirmed that there was no effect of configuration ($F(2,20) = 1.08$, $p = 0.36$, $\eta^2 = 0.10$) on the PSE. The results of Experiment 2 show that although perceived depth from disparity may be related to the figural interpretation of the stimulus, the effect appears to be strongly modulated by the direction of the disparity gradient, regardless of the methodology used.

In Experiment 1 and Experiment 2, when the configuration is rotated so that the disparity changes vertically, the target lines change from being vertical, to horizontal. In the original configuration when the target lines are vertical, and offset in depth, the disparity is constant along a given target line. In this case, when there is no linear perspective, the disparity of the horizontal connecting lines is only explicit at the endpoints, where they connect with the vertical target lines. However, when the configuration is 'rotated' so that the target lines are now horizontal, in the closed object condition, the connecting lines have slightly different orientations in the two eyes. This orientation difference, or orientation disparity, has been shown to provide strong stereoscopic depth information (Wheatstone, 1838). Greenwald and Knill (2009), suggest that orientation disparity provides efficient information regarding 3D orientation, and they assert that it may be useful when combined with estimates from monocular perspective cues. However, there is disagreement in the literature in regards to whether orientation disparities per se are responsible for depth perception. It is difficult to assert whether orientation disparity independently informs depth perception as positional and orientation disparity are confounded; features that give rise to different orientations in the two eyes also give rise to a vertical gradient of horizontal disparity (Bridge & Cumming, 2001; Adams & Mammasian, 2002). Still, there is some psychophysical evidence showing that the stereoscopic system uses orientation disparity (Blakemore, Fiorentini, & Maffei, 1972; von der Heydt et al., 1978; Ninio, 1985, Caganello & Rogers, 1993; Adams & Mamassian, 2002). For instance, Ninio (1985) used stereograms and put positional and orientation disparities into conflict, and found that the percept of slant was higher when orientation disparity was consistent with the slant of the stimulus. Similarly, Cagenello and Rogers (1993) showed that surfaces with the same amount of orientation disparity had similar detection thresholds, however when there was no orientation disparity the detection threshold for a slanted surface with a horizontal gradient of disparity was significantly higher, suggesting that the visual system uses orientation disparity as a binocular cue to depth.

Thus, is possible that the absence of orientation disparity is responsible for the reduction in perceived depth within the original (horizontal gradient) closed object. To assess this, in Experiment 3 I measured depth magnitude percepts for the connecting contours of the closed objects, in isolation.

EXPERIMENT 3

Introduction

The results of Experiment 1-2 suggest that the degraded depth effect reported by Deas & Wilcox (2014,2015) is dependant on the direction of the gradient of disparity. As outlined in the preceding section, it is possible that orientation disparity, not the disparity gradient within the figure, is responsible for the amount of depth perceived in the closed object conditions. In this study I separately assess the contribution of orientation disparity by presenting isolated lines with and without orientation disparity, this is equivalent to simply erasing the target line pairs in Experiment 1 and Experiment 2. As shown in Figure 10 these stimuli do not form a closed object, instead the disparity information is just at the endpoints (as in the closed object, vertical target line conditions, Figure 10A) or along the full line length via orientation disparity (as in the closed object, horizontal target line conditions, Figure 10C).

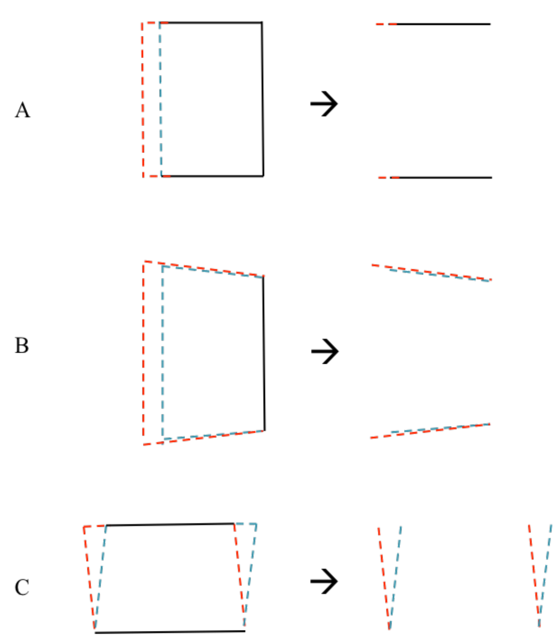


Figure 10 An illustration of three condition used in Experiment 3 (not to scale). (A) Horizontal target lines without orientation disparity (B) Horizontal target lines with orientation disparity,

and (C) Vertical target lines with orientation disparity. The left side of the illustration shows the closed object conditions used in Experiment 1, 2, and 4. For Experiment 3, the isolated line targets (right side of the illustration), were created by erasing the 'target lines' from the corresponding closed object conditions.

Observers

Eighteen observers participated in Experiment 3. Thirteen were relatively naïve stereoscopic observers. The remaining five participants were experienced observers who also participated in Experiment 1-2.

Stimuli

The target lines were composed of two white (59.1 cd/m^2) lines displayed on a mid-grey background (15.6 cd/m^2) positioned at the mid-point of the display. Each target line measured 2.20˚ x 0.1˚. Three stimulus configurations were created for each of the closed object conditions, as illustrated in Figure 11:

A. Horizontal Lines without Orientation Disparity: Two horizontal lines were presented, without the vertical target lines used in Experiment 1. Explicit binocular disparity was only present at the endpoints. Observers were asked to judge the depth between the left and right endpoints of the two lines.
B. Horizontal Lines with Orientation Disparity: Two lines were presented as in A, but in this case the two lines were oriented to be consistent with linear perspective (for the given test disparity and viewing geometry). Thus the lines contained disparity at the endpoints and orientation disparity along their extent. As in A, observers judged the relative depth of the disparate endpoints.

C. Vertical Lines with Orientation Disparity: Two lines were presented as in C, without the horizontal line targets used in Experiment 1. The two lines were orientated with a vertical gradient of horizontal disparity. As in B there was orientation disparity within the lines, however, there was no perspective information. In this case observers judged the relative depth of the top and bottom endpoints.

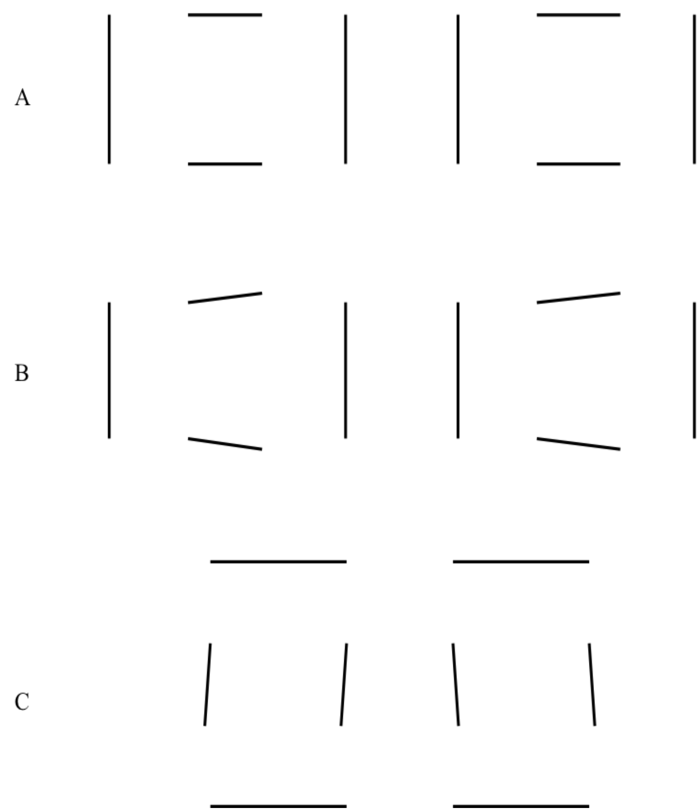


Figure 11. Sample stereograms used in Experiment 4. By crossing the eyes to fuse the outer pair of lines in each configuration one can appreciate the depth offset within the solid black central lines in each image pair. The black solid vertical lines in configuration (A) and (B), and the black solid horizontal lines in configuration (C) are identical, they have zero disparity, and were displayed to provide a reference. Each row depicts one condition: (A) Horizontal Lines without Orientation Disparity (B) Horizontal Lines with Orientation Disparity (C) Vertical Lines with Orientation Disparity.

On each trial, pairs of endpoints (left/right, top/bottom) of the two target lines were displaced by one of a range of crossed disparities (0.00˚, 0.05˚, 0.10˚, 0.15˚, 0.20˚, and 0.25˚), while the two reference lines were fixed at zero disparity. This range generated suprathreshold predicted depth percepts of approximately 0, 8, 16, 24, 32, and 40 mm.

Procedure

To help observers keep track of which pairs of endpoints were to be compared, Experiment 3 was conducted in two blocks. In one block observers judged the horizontal lines with and without orientation disparity (Figure 11A and B). In the other block they viewed vertical lines with orientation disparity (Figure 11C). For the stimuli shown in Figure 11A and B the task was to estimate the amount of depth between the left and right ends of the two horizontal contours. For the stimuli shown in Figure 11C the task was to estimate the amount of depth between the top and bottom of the two vertical contours. Observers used the haptic sensor strip (described in detail within the General Methods section) to record their depth estimates. At the beginning of each trial, a white (59.1 cd/m^2) fixation cross (1.5˚ x 1.5˚) was presented at the center of the screen for 750ms. On each trial, one end of the two central target lines (randomly selected) contained one of the six test disparities. For all three configurations, observers were asked to judge the amount of depth that they perceived between the endpoints of the target line pair. The two blocks were completed in pseudo-random order in one sitting. The block with the horizontal target lines (Figure 11A and B) consisted of 12 conditions (6 disparities x 2 configurations), and each condition was presented 10 times in random order, for a total of 120 trials. The block with the vertical target lines (Figure 11 C) consisted of 6 conditions

(6 disparities x 1 configuration), for a total of 60 trials. The stimulus remained on the screen from the beginning of the trial until the observer recorded their response.

Results and Discussion

Perceived depth, averaged across observers, for each configuration is plotted in Figure 12. As the disparity within the target lines increased, estimated depth increased for all three configurations. However, the amount of depth perceived within the target

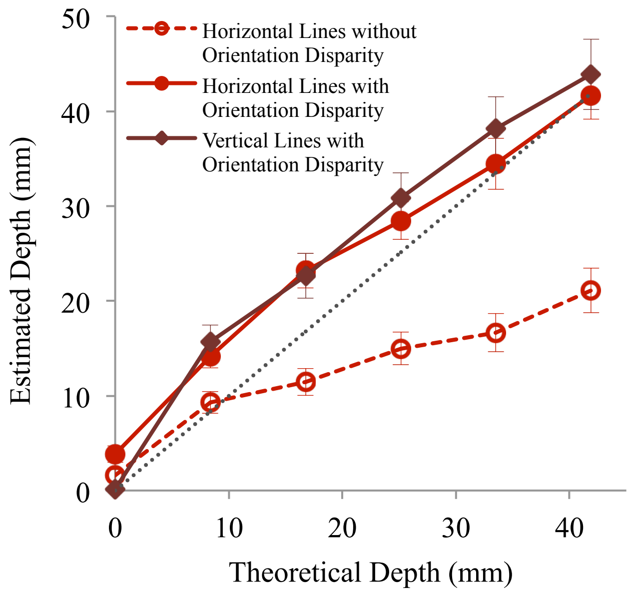


Figure 12. *Estimated depth (mm) is plotted as a function of theoretical depth (mm) for the three stimulus configurations: (A) Horizontal Lines without Orientation Disparity (dashed line, circles), (B) Horizontal Lines with Orientation Disparity (solid line, circles), and (C) Vertical Lines without Orientation Disparity (solid lines, diamonds). The dotted black line represents the geometrically predicted depth at each disparity. Error bars represent ± one standard error of the mean.*

contours was drastically reduced in the horizontal lines condition without orientation disparity. By comparison, when orientation disparity was present, a similar amount of depth was perceived in the horizontal, and vertical lines conditions, across the entire range of disparities. Moreover, estimates in these two configurations were consistently higher and more accurate than when the horizontal lines contained no orientation disparity. These observations were confirmed statistically. A repeated measures analysis of variance showed a significant interaction between Stimulus Configuration x Disparity, $F(7.65, 130.01) = 18.01$, $p<0.0001$, $\eta^2 = 0.52$ and a significant main effect of Stimulus Configuration, $F(2,34) = 22.30$, $p<0.0001$, $\eta^2 = 0.57$ and Disparity, $F(1.70, 22.83) = 198.96$, $p<0.0001$, $\eta^2 = 0.92$. Mauchly's test of sphericity showed that the assumption of sphericity was violated for the main effect of Disparity and for the interaction between Stimulus Configuration x Disparity, the Greenhouse-Geisser correction was applied to account for this. Pairwise t-tests and (using the BH procedure to control the false discovery rate) confirmed that the main effect of Stimulus Configuration was driven by significant differences between the horizontal lines without orientation disparity and the horizontal lines with orientation disparity condition at every disparity level ($p<0.001$ for the two lowest levels of disparity, and $p<0.0001$ for the remaining four levels of disparity), and between the horizontal lines without orientation disparity and the vertical lines with orientation disparity at every level of disparity ($p<0.05$, $p=0.01$, $p<0.002$ for the first three levels of disparity, respectively and $p<0.0001$ for the last three disparity levels). No comparisons between the horizontal lines and vertical lines with orientation disparity were significantly different, except at zero disparity ($p <0.001$). As mentioned above, prior to testing, observers were told that some configurations would be displayed with zero depth. Participants were instructed to respond by placing their index finger outside of the range of their responses, at the very top of the sensor strip, when they saw no depth. The stereotyped nature of this response accounts for the low variance observed at zero disparity, which drives the significant effect.

As shown in Figure 12, depth estimates for the horizontal lines presented without orientation disparity were consistently reduced. Importantly, in this condition, the lines were presented in isolation and they did not form a uniform closed object, yet perceived depth was significantly reduced. While there may have been some perceptual grouping in this condition due to similarity and/or collinearity, it is quite unlikely that it caused the reduction in perceived depth because i) depth estimates are accurate in the isolated line conditions in previous studies and ii) there is no such reduction when the horizontal line targets contained orientation disparity. Instead it appears that presence or absence of orientation disparity is an important determinant of suprathreshold depth in these studies.

In their studies, Deas and Wilcox (2014, 2015) isolated stereopsis by holding other monocular depth cues such as relative size, and perspective constant. Preliminary experiments using similar stimuli had shown that elimination of cue conflict between perspective and binocular disparity impacted the amount of reduction in perceived depth from closed configurations (Deas, 2015, unpublished thesis), but did not eliminate it. However as outlined above, the results of the current study suggest that orientation disparity can have a significant impact on perceived depth in these stimuli. Importantly, linear perspective and orientation disparities are closely related in these stimuli. That is, modification of the line targets used in Experiments 1 and 2 to add linear perspective consistent with binocular disparity necessarily introduces orientation disparity along the horizontal connecting lines. If orientation disparity (or lack thereof) plays a determining role in Experiments 1 and 2, it should be possible to eliminate the reduced depth percepts for closed stimuli with horizontal gradients of disparity simply by adjusting the line height to reflect correct linear perspective.

EXPERIMENT 4

Introduction

In physical stimuli, the displacement of the component lines in depth would result in differences in the relative height and width of the target. As outlined above in the stimuli used in Experiments 1 and 2, and by Deas & Wilcox (2014) the two vertical test lines had the same height. This ensured that the relative height of the lines could not be used to perform the task. However, fixing the line height in this way introduced a conflict between the depth defined by disparity and the depth defined by monocular perspective. That is, horizontal disparity information signalled that one line is closer than the other, but the relative size of and linear perspective information suggested that both lines lie on the same depth plane, making the signal ambiguous. This cue conflict was present in both the isolated line and closed object conditions, and therefore it was assumed that it would not play a key role in depth differences between them. However, as outlined in the preceding chapter, holding the vertical line height constant while they are shifted in depth creates an unusual change in disparity along the horizontal connecting contours. Under natural viewing conditions, these connecting contours would have slightly different orientations in the two eyes, and so provide orientation disparity. In Experiment 3 I show that orientation disparity can influence perceived depth in isolated line versions of these stimuli. If the absence of orientation disparity underlies the reduction in perceived depth seen in Experiments 1 and 2, introduction of linear perspective (and therefore orientation disparity along the horizontal connectors) to the stimuli used in Experiment 1 should restore perceived depth magnitude in the closed object conditions.

Observers

Eighteen observers participated in Experiment 4. Thirteen of them had no experience with psychophysical tasks. The remaining five participants were experienced observers.

Stimuli

The stimuli were modified versions of those used in Experiment 1 (Figure 5.1), and consisted of three configurations including: Isolated lines, Single Closed Object, and Two Closed Objects. At zero disparity, each vertical line measured 3.30˚ x 0.1˚, and was separated from its neighbour by 2.10˚. The stimuli comprised four white lines (59.1 cd/m^2) displayed on a mid-grey background (15.6 cd/m^2) positioned symmetrically about the mid-point of the display. To introduce linear perspective, the height of the vertical lines was adjusted based on perspective projection and the binocular viewing geometry. This calculation was performed individually for each observer, using his or her interocular distance.

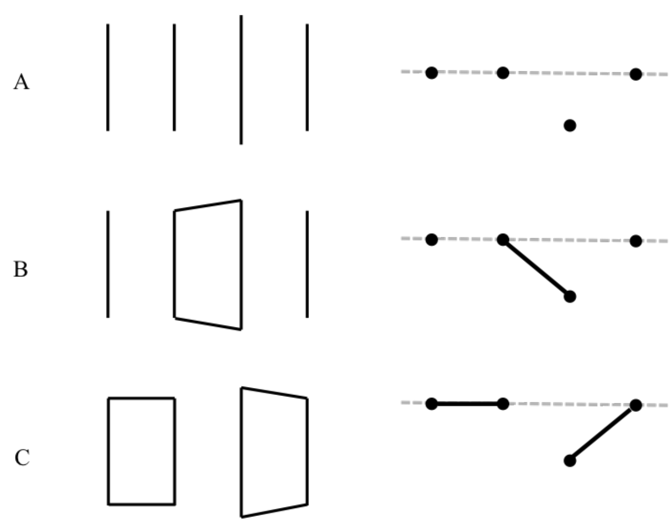


Figure 13. Monocular images of the three conditions used in Experiment 3: (A) Isolated Lines (B) Closed Object (C) Two Closed Objects. In this case the rightmost line of the central pair is

adjusted for linear perspective information (not to scale). The right side of the illustration shows a top-down view of the stimuli used in Experiment 4.

For an illustration of the stimuli (not to scale), see Figure 13. Three conditions were tested at a range of crossed disparities (0.00˚, 0.05˚, 0.10˚, 0.15˚, 0.20˚, and 0.25˚) and generated suprathreshold predicted depth percepts of approximately 0, 8, 16, 24, 32, and 40 mm.

Procedure

At the beginning of each trial, a white (59.1 cd/m^2) fixation cross (1.5˚ x 1.5˚) was presented at the center of the screen for 750ms. On each trial, one of the two target lines was presented at one of the six test disparities. The depth magnitude estimation task was used. For all configurations, observers were asked to judge the amount of depth between the central pair of lines. Experiment 4 was completed in one block, which consisted of 18 conditions (6 disparities x 3 configurations), with each condition presented 10 times in random order, for a total of 180 trials.

Results and Discussion

Perceived depth estimates for each condition were averaged across observers and plotted in Figure 14. For the three configurations that were modified to include monocular perspective (solid lines on the Figure 14), as the disparity between the target lines increased, estimated depth increased. There is a significant overestimation in the amount of depth perceived for the three stimulus configurations, across the entire range of disparities. Further, at all disparities depth estimates appear to be the same, irrespective of the configuration. These observations were confirmed statistically using a repeated measures analysis of variance. There was a significant main effect of Disparity, F(2.03,34.56) = 195.31, p<0.0001, η^2 = 0.91, and a significant interaction between Stimulus Configuration x Disparity F(3.81, 64.85) = 2.96, p<=0.01, η^2 =0.15. Given that Mauchly's test of sphericity was violated for the main effect of Disparity and the interaction between Stimulus Configuration x Disparity, the Greenhouse-Geisser

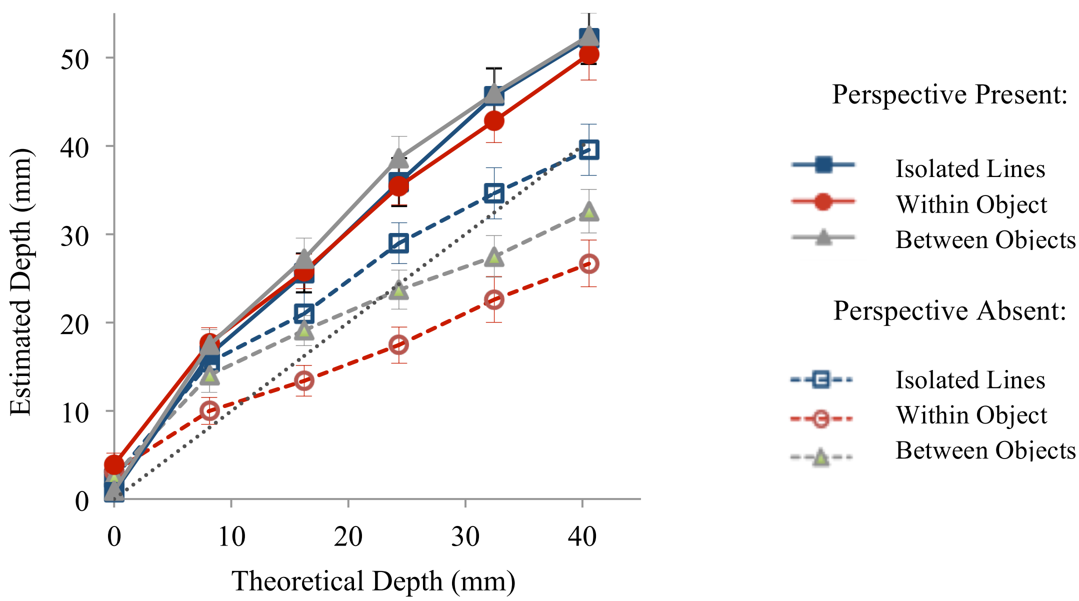


Figure 14. Estimated depth (mm) is plotted as a function of theoretical depth (mm) for the three stimulus configurations with linear perspective: Isolated Lines (squares), Single Closed Object (circles), and Two Closed Objects (triangles). Results for Experiment 1 (without linear perspective) are included for comparison, and are represented by dashed lines. The dotted black line represents the geometrically predicted depth at each disparity. Error bars represent ± one standard error of the mean.

correction was applied. There was no significant main effect of Stimulus Configuration, F(2,34) = 0.79, p=0.46, η^2 = 0.04. Pairwise t-tests (using the BH procedure to control the false discovery rate) revealed that the interaction was driven by significant differences between the Isolated Lines and Single Closed Object condition at zero disparity (p<0.05), and by differences between the Single Closed Object and Two Closed Objects condition at two disparity levels, 0.20˚, and 0.25˚ (p<0.01 and p <0.05, respectively). No other comparisons were significantly different. As predicted, these results show that the reduction in perceived depth seen in Experiments 1 and 2 is eliminated when orientation disparity is present along the horizontal connecting lines. Deas (2015, unpublished thesis) found a small difference remained between the closed object and isolated lines conditions even with the addition of linear perspective, however I see no such difference here. This inconsistency could be simply due to the different groups of observers tested, however it is difficult to know. Irrespective of the cause, the data suggest that the grouping effect reported by Deas & Wilcox (2014) is not a robust phenomenon, particularly in the presence of additional, congruent, depth cues. Another notable property of the results shown here is the large increase in perceived depth, well above the amount predicted by binocular viewing geometry, at the entire range of disparities tested.

The overall increase in perceived depth magnitude may be due to individual differences in the dependence on specific depth cues. Studies have shown that in the presence of multiple depth cues, some observers rely primarily on perspective information, others are able to use binocular disparity in isolation, still others have shown to use a combination of both perspective and binocular disparity (Allison & Howard, 2000, Sato & Howard, 2001; Zalevski et al., 2007). Observers that use binocular disparity in isolation show little or no change in depth estimates when perspective is varied. On the other hand, people that rely exclusively on perspective information may show large changes in the amount of depth perceived when viewing stimuli with and without perspective (Sato & Howard, 200l; Hartle & Wilcox, 2015). This is particularly true for individuals that do not have a lot of experience with stereoscopic tasks (Hartle & Wilcox, 2015), which was the case for majority of the observers that participated in this series of experiments. Additionally, depending on the viewing distance, studies have shown that observers make systematic errors in matching the depth of stereoscopic objects according to the objects' height (Vienne, Blonde, & Mamassian, 2014). Observers viewing stereoscopic images tend to overestimate depth when objects are displayed in front of the screen plane (Johnston, 1991). Still, it is unclear why the presence of multiple depth cues resulted in such substantial overestimates of depth magnitude, for all three test conditions.

The results of Experiments 1-4 were obtained using virtual stimuli in cue-impoverished environments. From this particular series of experiments, it appears that there are several factors that impact perceived depth from simple virtual stimuli. Further, these factors interact with perceptual grouping in a complex manner, and can eliminate the reported disruptive effect of grouping. Using the line stimuli shown here, it is difficult to separate the impact of perspective and orientation disparity on perceived depth. However the results of Experiment 3 suggest that orientation disparity plays a larger role in modulating perceived depth than perspective cues. However, there is ample evidence that our perception of depth in full-cue environments is both accurate and precise (Buckley & Frisby, 1993; Bradshaw, Hibbard, & Gillam, 2002; Allison, Gillam, & Vecellio, 2009). To evaluate whether the distortions in perceived depth that are apparent when using virtual, cue-impoverished stimuli are also apparent in the presence of multiple, consistent 2D depth cues, in Experiment 5 I assessed perceived depth magnitude using physically rendered stimuli, with the same overall dimensions as the simulated targets presented in Experiments 1-3.

EXPERIMENT 5

Introduction

In Experiments 1-4, stimuli were presented virtually on LCD displays, using a mirror stereoscope. It is possible that within virtual environments, the absence of multiple, consistent depth cues make stereoscopic depth estimates more prone to phenomena such as object-based grouping and cue-conflicts. Research has consistently shown that in the presence of multiple, consistent cues to depth, systematic errors in depth estimation is considerably reduced or entirely eliminated. For example, Loomis et al. (1996) demonstrated that depth intervals were underestimated in a reduced cue-environment where observers were asked to match a depth interval (along the z-axis) to a lateral extent (along the x-axis). In contrast, when the observers were asked to walk across the same interval in a full-cue naturalistic environment, their physical movement within the environment showed no such bias (Loomis et al., 1996). Bradshaw et al. (2002) used a pointing task to assess the participants' perception of surface orientation at various points along a surface. When participants were instructed to point at stereograms that represented surfaces slanted in depth either about the horizontal axis or vertical axis, there was a clear anisotropy where participants indicated much steeper surfaces when slant was about the horizontal axis (Bradshaw, et al., 2002). The same pattern of results was obtained for a depth estimation task (Bradshaw, et al., 2002). However, when using real surfaces, with redundant depth cues performance was near veridical for the surfaces oriented about the vertical and horizontal axes (Bradshaw et al., 2002).

In these natural settings where multiple objects are visible, depth perception tends to be much more consistent with geometric predictions, even for stereoscopically defined stimuli (Gillam, Flagg, & Finlay, 1984; Rogers & Bradshaw, 1994; Bradshaw et al., 2002). If this is true, then the same result would hold for the phenomenon described here, and there should be no reduction in the amount of depth perceived within a closed object slanted with a horizontal gradient of disparity for physical targets. In Experiment 5 we 3-D printed plastic targets that closely matched those used in Experiments 1-3 above, and assessed depth magnitude using a custom built physical stereo robot (PSR).

Observers

Twelve observers participated in Experiment 5. Of these, nine were naïve stereoscopic observers, of whom seven participated in Experiment 1 and 3. Two were experienced observers, who also participated in previous experiments.

Stimuli

The stimuli for this experiment were designed to replicate those from the preceding studies and those used by Deas and Wilcox (2014). Targets consisted of 3D-printed vertical posts (plastic frames), in two stimulus configurations: two vertical isolated lines and a single closed object configuration (Figure 15). The targets were painted white (16.5 cdm^2) and were positioned symmetrically about the mid-point of the apparatus on a black background (3.00 cd/m^2). In the zero disparity test condition, each target vertical line measured 3.30˚ x 0.1˚, and the pair of vertical lines was separated by 2.10˚. In order to create disparity, the plastic frames were printed with a range of physical widths between the vertical lines. Each frame was then carefully slanted into position onto a platform, so that the left line of each frame was fixed at zero disparity while the right line was displaced according to the disparity level. When viewing the stimulus, this ensured that the vertical lines were always separated by 2.10˚. The targets were viewed at a fixed viewing distance of 74 cm. These dimensions closely matched the computer-generated line stimuli used in Experiment 1. To control the height of the target lines, the lower portions of the plastic figures were painted black (3.00 cd/m^2 to match the luminance of the background). The stimuli were printed with small notches at the base, which were then affixed onto a wooden platform. The platform was spray-painted black (0.01 cd.m^2), and tiny slots that matched the size of the notches were cut into the platform, so the plastic figures could be properly secured. All of the stimuli were

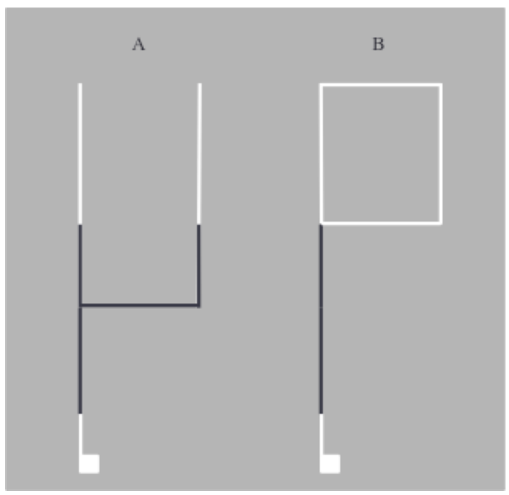
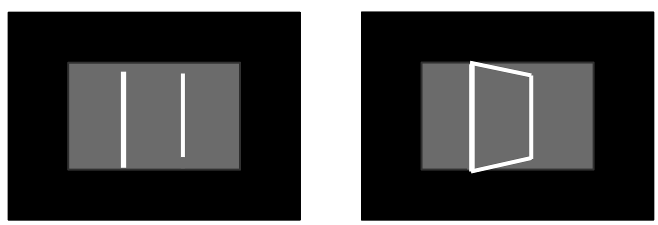


Figure 15. Illustration of the two stimulus configurations used in Experiment 5. This image is showing the configurations before they were mounted onto the PSR: (A) Isolated Lines (B) Closed Object. The lower section of the targets was painted black, and this region was for the most part occluded from the observers' view. Tiny square notches at the base of the configurations were used to affix the targets onto the base (wooden platform).

then affixed onto the platform, which was then mounted onto a linear actuator within the enclosure. An aperture that measured 3.36 cm by 5.24 cm was placed 60 cm in front of the observer, through which they could see the stimuli. On each trial, the actuator was moved along the x-axis (across the width of the PSR), and when the correct stimulus was in place, the lights came on, illuminating it. Two conditions were tested at a range of uncrossed disparities (0.00˚, 0.075˚, 0.15˚, 0.225˚) and generated predicted depths of approximately 0, 12, 24, and 36 mm, this range encompasses the disparity levels used in the previous experiments. Two configurations were created, as illustrated in Figure 16 (showing the observers' view):

A. Isolated Lines: Two high-contrast white (16.5 cdm^2) vertical lines were presented with a horizontal disparity offset. Observers judged the relative depth between the two vertical target lines.

B. Closed Object (Within Object): The vertical lines were connected to form a rectangle. The target lines were the same as in A, but now they formed the edges of a single closed rectangle.



A B

Figure 16. Illustration of the two stimulus configurations used in Experiment 5, showing the observer's view point: (A) Isolated Lines (B) Closed Object.

Apparatus

The PSR is an aggregate of computer-controlled motion-stages built within an enclosure (see Figure 17 for illustration of the apparatus). Actuators are mounted onto an optical bench at the bottom of the enclosure, and connected to the top of the frame. Each actuator had a positional repeatability of +/- 0.025 mm and a positional error of 0.4 mm per meter of travel (for the purposes of this experiment, the error was negligible) (Hartle & Wilcox, 2016), and was controlled by a Galil DMC-4050 motion controller. All of the targets were affixed on a wooden platform that was mounted on the linear actuator along the width (1.17m) of the PSR for movement along the x-axis. LED light fixtures were placed behind the viewing aperture, through the top of the PSR frame, and were used to illuminate the targets (Hartle & Wilcox, 2016). Importantly, a Python script was used to run the experiment and it controlled the linear actuator and the LEDs; this ensured precise timing of illumination (and therefore the visibility) of the stimuli. The LEDs were only illuminated at the start of each trial, and automatically turned off once the observer made their response. Observers viewed the stimuli through an aperture placed at one end of the entire enclosure, and their head was stabilized by a chinrest.

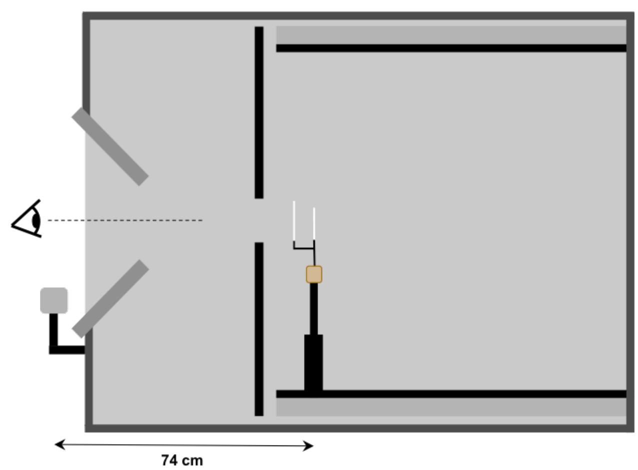


Figure 17. A schematic of the PSR (image adapted from Hartle & Wilcox, 2016), viewed from the side, depicting the enclosure, the linear actuator, and the wooden platform to which the target stimuli are attached. Observers sit to the left of the enclosure, and their head position is stabilized by the use of a chin rest. Adjustable panels are placed at an angle to restrict the view to the interior of the enclosure. The black board, with the viewing aperture is positioned in between the observer and the physical targets. The view distance, from the observer to the targets is 74cm.

Procedure

At the beginning of each trial, two small LEDs (green) were presented 74cm from the observer for 750ms. On each trial, one of two stimulus configurations was displayed at one of the four test disparities, in random order. The depth estimation task was used, and on all trials observers were asked to judge the relative depth between vertical target lines. Observers used the haptic sensor strip (described in the General Methods section) to record their estimates, and pressed a button on a gamepad when they were ready to submit their response. As in the previous experiments, observers were instructed to place their index finger at the far end of the sensor strip to indicate when they perceived zero depth between the two vertical target lines. Audio feedback was provided when sufficient pressure was applied to the sensor strip. Observers were able to adjust their finger on the strip until they were satisfied with their response. Once the response was recorded, the lights within the PSR were turned off, and the motion platform was repositioned to initiate the next trial. Each 20-minute session consisted of 8 conditions (4 disparities x 2 configurations), with each condition presented 10 times in random order, for a total of 80 trials.

Results and Discussion

Figure 18 shows the amount of depth estimated for the isolated line and closed object conditions plotted as a function of physical depth in mm. As the amount of physical depth increased, the amount of estimated depth increased monotonically. There was a slight overestimation in the magnitude of depth at the largest disparity but depth estimates were unaffected by configuration and overall the estimates were very accurate; these observations were supported statistically. The data were analyzed using a repeated measures analysis of variance. The results of this analysis demonstrated a significant main effect of Physical Depth, $F(1.46, 16.02) = 115.21$, $p<0.0001$, $\eta^2 = 0.91$, confirming that as the physical depth between the target lines increased in both configurations, the amount of perceived depth increased. Mauchly's test of sphericity showed that the assumption of sphericity was violated for the main effect of Physical Depth, and so the Greenhouse-Geisser correction was applied. There was no significant effect of Stimulus Configuration, $F(1,11) = 0.16$, $p=0.70$, $\eta^2 = 0.01$, and no interaction between Stimulus

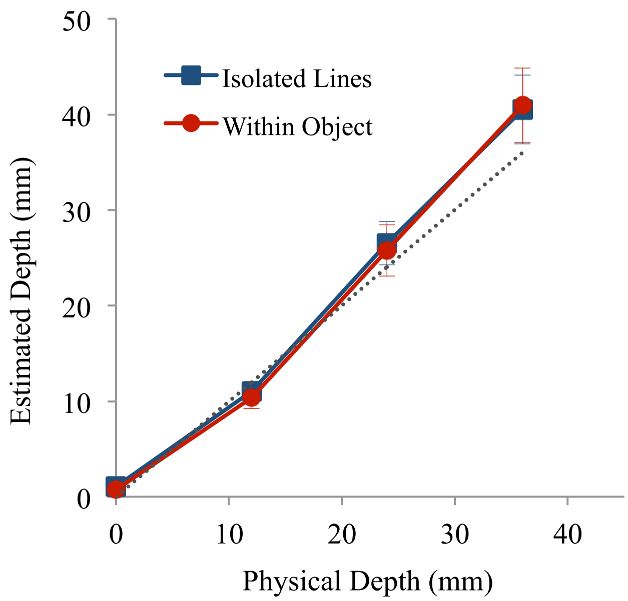


Figure 18 Estimated depth (mm) is plotted as a function of physical depth (mm) for the two stimulus configurations: Isolated Lines (blue), and Closed Object (red). The dotted black line represents physical depth. Error bars represent ± one standard error of the mean.

Configuration x Physical Depth, $F(1.79, 19.68) = 0.27$, $p=0.85$, $\eta^2 = 0.02$. Pairwise t-tests (using the BH procedure to control the false discovery rate) revealed that there was no significant difference between the stimulus configurations as a function of physical depth.

Experiment 5 demonstrates that when viewing physical targets in a natural viewing environment, depth magnitude estimates are accurate over the range of disparities tested in Experiments 1-4. Moreover, there was no difference between the estimates obtained in the isolated line vs. closed object configurations. This suggests that the availability and congruence of additional, reliable depth cues with binocular disparity is critical for minimizing distortions in perceived depth.

A potentially significant difference between the depth cues available in simulated vs. physically disparate targets is the relationship between accommodation and convergence. In physical environments under normal conditions accommodation and vergence covary. However, in stereoscopic display systems, accommodation is always fixed on the screen plane, while vergence may vary substantially. This so-called vergence-accommodation conflict is most salient at near viewing distances, and has been shown to influence the accuracy and precision of depth judgements when viewing more natural stimuli (Hoffman, et al., 2008; Okada, et al., 2005; Inoue & Ohzu, 1997). Thus it may play a role in the improved accuracy in depth estimates in Experiment 5. Even for simple stereoscopic targets, multiple factors seem to contribute to determining suprathreshold depth, including binocular disparity and monocular cues to distance.

GENERAL DISCUSSION

Summary

The series of experiments described here assessed whether previously reported distortions in perceived depth are generalizable and robust. Specifically, this research was motivated by the recent experiments of Deas and Wilcox (2014, 2015) who showed that perceived depth was directly dependent on perceptual grouping by closure (Deas and Wilcox 2014).

In Experiment 1, I first replicated the experiments performed by Deas and Wilcox (2014). The pattern of results was similar when the target lines were vertical (gradient of disparity was horizontal). Surprisingly, I found that the reduction in perceived depth seen in the original closed object condition (that contained a horizontal gradient of disparity) disappeared when the closed object contained a vertical gradient of disparity. This result cannot be explained by grouping or by the presence of depth cue conflict (as these factors are equivalent in both sets of stimuli). To ensure that the results obtained in Experiment 1 were not due to the task used, in Experiment 2 I assessed the impact of grouping and the direction of the disparity gradient with a 2IFC discrimination task, with the same stimuli and observers. The pattern of results was the same in the two experiments, which suggests that a factor other than perceptual organization is modulating perceived depth for these stimuli. While this other factor could be the direction of the disparity gradient, it could also be the presence/absence of orientation disparity along the connecting contours.

In Experiment 3 I assessed the impact of the change in disparity along the contour (orientation disparity), by presenting the connecting contours of the closed objects alone. In this study observers were asked to simply judge the relative depth between the endpoints (left/right or top/bottom) of the pair of lines. I found that depth magnitude estimates were equivalent and close to geometric predictions when the stimuli contained a change in disparity along the contour. This was irrespective of the direction of the horizontal disparity gradient. However, depth estimates were significantly reduced when there was no change in disparity along the horizontal contour. In fact, the reduction in depth in this condition was very similar to that seen in the closed object condition in Experiment 1. Critically, when the horizontal contour contained a change in disparity along the contour, depth estimates were restored. The results of this experiment provides strong evidence that the reduction in suprathreshold depth percepts is not necessarily contingent on perceptual grouping of elements to form an object, rather the degradation is modulated by the presence or absence of orientation disparity.

In Experiment 4 I assessed the impact of conflict with linear perspective in the original stimuli used by Deas and Wilcox (2014). Simply correcting linear perspective in the targets eliminated the reduction in perceived depth, but caused a substantial depth overestimation for all three configurations. Modifying the closed object by adjusting line height to be consistent with linear perspective creates a change in disparity along the horizontal connectors, which, as shown in Experiment 3, contributes to the resultant loss of perceived depth.

Experiments 1-4 used restricted cue paradigms within virtual environments to specifically understand stereoscopic mechanisms. To assess whether the disruptive effects shown here occur in full-cue environments, in Experiment 5, I replicated Experiment 1 (vertical target lines with a horizontal gradient of disparity) using physical stimuli. The results showed that depth estimates for physical, cue-consistent stimuli were accurate, and perceived depth was not affected by configuration.

Taken together, the results of these experiments suggest that even for simple stereoscopic targets, multiple factors determine suprathreshold depth percepts and the reduction in perceived depth observed previously is not exclusively dependent on perceptual organization. In the current series of experiments I identified and evaluated factors related to the strength of the disparity signal (the presence or absence of depth cue conflicts and orientation disparity). I discuss this below.

Strength of the disparity signal

When there is a vertical gradient of disparity between the target lines for the closed object condition, in addition to the change in gradient, there is orientation disparity along the vertical connecting contours. Orientation disparities are larger for vertical gradients of horizontal disparity than for horizontal gradients of disparity (Blakemore, Fiorentini & Maffei, 1972; Cagenello & Rogers, 1993) (Figure 19). When the rectangle is slanted with a horizontal gradient of disparity, there is no change in disparity (orientation disparity) along the horizontal connectors of the rectangle (see Figure 19A), and the disparity is only present at the endpoints of the connecting contours. In contrast, when the same rectangle is slanted with the disparity relationships maintained, the disparity varies along the vertical connectors, providing a less ambiguous disparity signal (see Figure 19B). Critically, disparity is present along the vertical contours regardless of whether the rectangle is slanted with a horizontal or vertical gradient of disparity, however the change in disparity present when the rectangle is rotated with a vertical gradient of disparity may

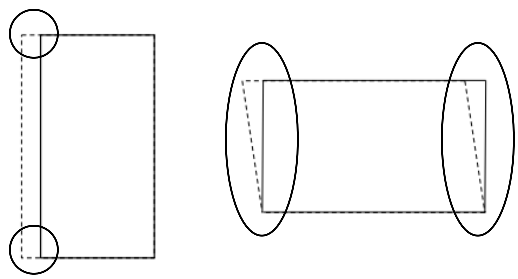


Figure 19: An illustration of the difference in orientation disparities for a rectangle rotated with a horizontal gradient of disparity (A), and a rectangle rotated with a vertical gradient of disparity (B). In a., there is a jump in disparity, and it is only present at the end points. In b., there is a constant change in disparity along the vertical connecting contours of the rectangle.

provide an additional cue to the slant of the surface. Thus the presence of orientation disparity effectively strengthens the disparity information within the stimulus and therefore the percept of depth. In fact, observers judged the depth of the end-points of isolated connecting contours, with orientation disparity, just as accurately as they did when disparate target contours were also present. This additional disparity information makes the surface resistant to disruptions in perceived depth. I argue that the reduction in perceived depth in the rectangle slanted with a horizontal gradient of disparity is not exclusively due to cue-conflict between 2D and stereoscopic depth cues. Instead, the absence of orientation disparity makes the stereoscopic system more susceptible to systematic errors, either under or over estimates. Orientation disparity has been shown to be a source of useful information for depth judgments. Studies have shown that the magnitude of orientation disparity is directly related to the perceived magnitude of surface slant, and computational investigations suggest that orientation disparity can be computed by binocular neurons with receptive fields that are specifically tuned to slightly different orientations in each eye (Mitchell & O'Hagan, 1972; Ninio, 1985; Gillam &

Rogers, 1991; Cagenello & Rogers, 1993; Blakemore, Fiorentini, & Maffei, 1972; von der Heydt, Hanny & Dursteler, 1981; Nelson, Kato, & Bishop, 1978).

Slant Perception

Evidence from early research on slant estimation suggests that the direction of the disparity distribution within a stimulus significantly impacts their suprathreshold appearance (Wallach & Bacon, 1976; Rogers & Graham, 1983). The visual system is relatively insensitive to smooth gradients of disparity, specifically along the horizontal direction (Wallach & Bacon, 1976; Rogers & Graham, 1983; Mitchison & Westheimer, 1990; Cagenello & Rogers, 1993; Hibbard & Langley, 1998; Mitchison & McKee, 1990). The slant in depth of these horizontal gradients of disparity is consistently underestimated (Gillam, 1968; Gillam, Flagg & Finlay, 1984; Stevens & Brookes, 1988; Rogers & Cagenello, 1989) and the percept of depth is slower to develop than when the same gradient occurs in the vertical direction (van Ee & Erkelens, 1996). Our data support the literature in that stereoscopic slant around the horizontal axis was much greater than perception around the vertical axis (Experiment 1 and 2). Explanations for the anisotropy typically refer to the presence of cue conflict with perspective (Ryan & Gillam, 1994; Zalevski, Henning, & Hill, 2007), or the insensitivity of the stereoscopic system to smooth horizontal disparity gradients (Gillam, Flagg, & Finlay 1984; Brooks & Stevens, 1989). Cagenello and Rogers (1993) provided evidence showing that orientation disparities are used by the stereoscopic system, and underpin the anisotropy in slant detection. However, there has been debate regarding the matter (Gillam & Ryan, 1992; Bradshaw, Hibbard, & Gillam, 2002). For instance, Gillam & Ryan (1992) used various patterns of grids (composed of vertical, horizontal, and diagonal lines), and found that in the diagonal line condition, where orientation disparities were identical regardless of the slant about the horizontal or vertical axis, perceived slant was much greater for slant around the horizontal axis compared to slant around the vertical axis. Rather than differences in orientation disparities within the surface, they suggest that the anisotropy may be the result of differences in processing image shear vs. compression disparities (Wallach & Bacon, 1976; Rogers & Graham, 1983; Gillam & Ryan, 1992; Bradshaw, Hibbard, & Gillam, 2002). Additionally, they conclude that configural properties of the surface make an important contribution to the perceptual anisotropy and that these factors are independent of the presence of orientation disparity and conflicting perspective cues (Gillam & Ryan, 1992). Similarly for the stimulus configurations that I used, the attenuation of perceived slant was not simply tied to the presence of bounding contours that create the interpretation of a common surface, instead it seems that perceived slant was determined by multiple factors, including but not limited to, configural properties of the stimulus, and the strength of the disparity signal.

Moreover, it is important to note that there are large individual differences in the strength of the horizontal/vertical slant anisotropy (Hibbard et al., 2002). Hibbard et al., 2002 found that although sensitivity to stereoscopically defined slant about the horizontal axis was approximately 2.5 times greater than sensitivity to slant about the vertical axis, there was wide variation in the degree of the anisotropy across observers. This was attributed to multiple factors, including the integration of disparity information with perspective and other depth cues (Gillam, 1968; Steven & Brookes, 1988; Mitchison & McKee, 1990; Gillam & Ryan, 1992), differences between initial and subsequent measurements of disparities (Tyler, 1991), and individual differences pertaining to variations in sensitivity to orientation differences (Hibbard et al., 2002).

Natural Stimuli

The reduction in perceived depth between parts of a single object could significantly disrupt our ability to interact with objects in the natural environment. However, as shown in Experiment 5, perception of depth in physical cue-consistent targets is very accurate. Several studies show that perception of depth in physical stimuli is accurate despite (or perhaps because of) the complexities within natural scenes (Frisby, Buckley, & Duke 1996; Allison, Gillam & Vecellio, 2009; McKee & Taylor, 2010). It seems that the abundance of redundant depth cues typically present in physical targets, allow human beings to compensate for systematic errors that can arise when stereopsis is presented in isolation. For example, Taylor and McKee (2010) showed that naïve observers had higher thresholds when asked to discriminate the relative depth of stereoscopic bars compared with real metal rods. This finding suggests that the results of naïve observers should be interpreted with caution when they are asked to judge the relative depth of virtual targets (Taylor & McKee, 2010; Hartle & Wilcox, 2016).

The interaction of stimulus configuration and depth cue-conflicts can produce substantial errors in the perceived shape and position of virtual 3D stimuli. When all depth cues are consistent, perceived depth is not disrupted. Based on the results of this thesis, we recommend that virtual stimuli be designed with multiple, redundant cues to depth, in order to minimize the disruptive effects on perceived depth magnitude, which can significantly impact judgments of depth from stereopsis.

Conclusion

In this dissertation I have shown that reduced depth percepts are not always a consequence of perceptual grouping. As shown by Deas and Wilcox (2014) it is possible to partially isolate the effects of grouping on suprathreshold depth perception. However, several factors contribute to the perception of depth from disparity. Stereopsis is modulated by a complex set of interactions between depth from disparity, monocular depth cues, and orientation disparity. Even when using simple line stimuli, the interactions between low-level disparity processes and higher-level perceptual interpretations of the scene can produce substantial errors in perceived depth (both over and under estimates). These errors can be corrected by ensuring that monocular depth cues are consistent with binocular disparity. It is important that when investigating stereoscopic depth perception, investigators keep these interactions in mind.

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