Gestalt grouping via closure degrades suprathreshold depth percepts

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It is well known that the perception of depth is susceptible to changes in configuration. For example, stereoscopic precision for a pair of vertical lines can be dramatically reduced when these lines are connected to form a closed object. Here, we extend this paradigm to suprathreshold estimates of perceived depth. Using a touch-sensor, observers made quantitative estimates of depth between a vertical line pair presented in isolation or as edges of a closed rectangular object with different figural interpretations. First, we show that the amount of depth estimated within a closed rectangular object is consistently reduced relative to the vertical edges presented in isolation or when they form the edges of two segmented objects. We then demonstrate that the reduction in perceived depth for closed objects is modulated by manipulations that influence perceived closure of the central figure. Depth percepts were most disrupted when the horizontal connectors and vertical lines matched in color. Perceived depth increased slightly when the connectors had opposite contrast polarity, but increased dramatically when flankers were added. Thus, as grouping cues were added to counter the interpretation of a closed object, the depth degradation effect was systematically eliminated. The configurations tested here rule out explanations based on early, local interactions such as inhibition or cue conflict; instead, our results provide strong evidence of the impact of Gestalt grouping, via closure, on depth magnitude percepts from stereopsis.

Introduction

Under ideal conditions, the human eye is able to discriminate relative disparity with remarkable precision. For example, discrimination thresholds for a pair of vertical lines can be as low as a few seconds of arc for practiced observers (Westheimer, 1979; Westheimer & McKee, 1977). However, perceived depth cannot always be predicted directly from low-level disparity processing; rather midlevel effects of configuration also play an important role. For instance, when horizontal lines are added above and below the vertical line pair to form a closed rectangular object, there is a dramatic loss of sensitivity (McKee, 1983; Mitchison & Westheimer, 1984; Westheimer, 1979). It appears that when the vertical lines are perceived as part of a unified object, the stereoscopic system is unable to extract the disparity information with the same precision. This occurs despite the fact that the same local disparity signal is present.

Subsequent studies have shown that the disruptive effects of figural closure are robust for stimuli that exhibit both explicit and implicit spatial connections between target end points (Fahle & Westheimer, 1988; Mitchison & Westheimer, 1984; Zalevski, Henning, & Hill, 2007). For instance, McKee (1983) changed the position of the horizontal lines that connect the vertical test pair (to form "H" and ladder configurations), and consistently found degraded sensitivity. Mitchison and Westheimer (1984) removed the central part of a closed rectangle to create a bracket configuration and found thresholds were very similar to those obtained using a fully-closed object. The threshold elevation seen for these simple configurations has been variously attributed to cue conflict, feature saliency, and grouping. Zalevski et al. (2007) show that the effect can be reduced when perspective cues are consistent with disparity, though this improvement only occurs for some observers. Thus the presence of cue conflict cannot fully account for the phenomenon. Mitchison and Westheimer (1984) analyze their results in terms of interactions between salient features (where salience is a weighting term that varies with distance), whereas McKee (1983) discusses these phenomena in the context of grouping. In preliminary studies we repli-

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cated this phenomenon and ruled out local explanations based on cue conflict and saliency (Deas & Wilcox, 2012). In this paper we use the same modified configuration and assess configural impacts on perceived depth magnitude. In addition, we explicitly manipulate Gestalt grouping cues to determine their role in the reduction of perceived depth in these configurations.

From its outset, the originators of the Gestalt movement were aware of the potentially important role of the third dimension (depth) in perceptual organization of visual space. In his chapter devoted to the organizational theory of three-dimensional space, Koffka (described in Hartmann, 1935, pp. 105 and Koffka, 1935, pp. 161) argues that "three-dimensional shapes are matters of organization in the same way as two-dimensional ones, depending on the same kind of laws" (p.161). He goes on to describe experiments by Kopfermann (1930) who provided multiple demonstrations of configural influences on the recovery of 3D shape in both 2D planar stimuli and across multiple depth planes (in 3D). In one of her studies, Kopfermann (1930) drew different components of closed line figures (e.g., fragments of triangles or rectangles) on glass plates and slotted the segments into a light-proof box at separations of 2 cm. She found that the perceived relative depth of the figure's components critically depended on the perceived coherence of the figure. If the stimulus was seen as distinct unconnected units, the relative depth of the individual fragments was veridical. On the other hand, if the line patterns formed a single object, the percept of depth was eliminated (for summary of this work see Hartmann, 1935). The Gestaltists argued that the good Gestalt created via the 2-D grouping cues triumphed over the disparity signal provided by stereopsis (Hartmann, 1935; Koffka, 1935). Kopfermann's experiments provide an important illustration of the powerful effects of figural grouping on the perception of depth, and arguably her results reflect the same processes that degrade depth percepts in the work of McKee, Westheimer, and others described above. It is also likely that her observations are related to more recent experiments by Liu, Jacobs, and Basri (1999); Yin, Kellman, and Shipley (2000); and Hou, Lu, Zhou, and Liu (2006). These researchers have manipulated isolated grouping cues in amodal completion arrangements and assessed their effects on disparity thresholds. For example, Liu et al. (1999) demonstrated that the shape of a bounding contour (convex vs. concave) determined whether a figure was perceived as coherent, which consequently influenced disparity discrimination thresholds. In Yin et al.'s (2000) experiments they showed that integration of flanking surfaces behind an occluder reduced disparity sensitivity (d'). Integration was critically dependent on the similarity of visible surface features (e.g., color and texture) as well as the presence of collinear and relatable edges. Hou et al. (2006) manipulated occlusion arrangements to influence the perceived amodal completion of two bars, and showed that in the presence of such completion disparity sensitivity was degraded. These and related studies provide convincing evidence that figural interpretation constrains depth thresholds and provide important evidence against a strictly hierarchical model of disparity processing, as low-level operations are clearly modulated by midlevel contextual effects. As Yin et al. (2000) suggest, this may be related to object or surface-based disparity smoothing (see Marr & Poggio, 1976; Mitchison & McKee, 1987a, 1987b; Mitchison, 1988). The disruptive effect of midlevel configural organization was also highlighted in the work of Lu, Tjan, and Liu (2006) who showed that observers' interpretation of coherent biological motion in point-light figures had a similar detrimental effect on depth discrimination thresholds.

The experiments described above document losses in precision of depth discrimination at threshold, which inherently reflects the degree of noise (internal and external) in the system (see Pelli, 1985). However, to date no one has assessed what impact (if any) these configural influences on stereoscopic thresholds have on the *suprathreshold* appearance of the stimuli. That is, does the perceived separation in depth of two isolated elements change when they are connected to form parts of a closed object?

In the experiments described here we use a modified version of McKee's (1983) stimulus to assess suprathreshold depth magnitude percepts for configurations that promote the percept of segmented lines or closed objects. The simplicity of this stimulus makes it relatively straightforward to isolate and directly compare the effects of grouping versus segmentation on perceived depth. In Experiment 1, we demonstrate that perceptual grouping (closure) has a significant impact on suprathreshold percepts of depth magnitude, which cannot be explained via local interactions. In Experiment 2, we systematically manipulate grouping cues to modulate perceived closure and as a consequence depth percepts from disparity.

Experiment 1

Methods

Observers

Eighteen observers participated in Experiment 1. Eleven (including the two authors) were experienced stereoscopic observers. Seven were paid undergraduate students with no prior experience with psychophysical

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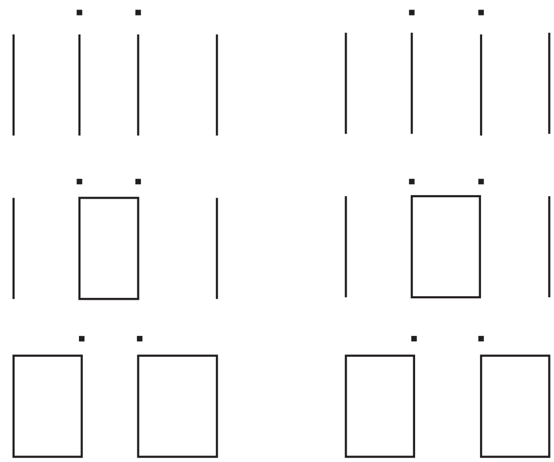

Figure 1. Stereograms of the stimulus configurations used in Experiment 1 arranged for crossed fusion. Observers judged the relative depth of the two central vertical lines in each condition. Each row depicts one condition: (A) Isolated lines, (B) Closed Object, and (C) Segmented Objects. In each of the above stereopairs, the rightmost line of the central target pair has the same crossed disparity. See text for additional stimulus details.

tasks. The research described here was evaluated and approved by the research ethics board at York University and followed the tenets of the Declaration of Helsinki. All observers had normal or corrected-to-normal visual acuity and were able to discriminate disparity of at least 40 seconds of arc on the Randot stereoacuity test.

Stimuli

The stimulus was composed of four identical vertical lines, positioned symmetrically about the midpoint of the display. Three conditions were created by manipulating which pairs of lines were connected with horizontal lines to form closed objects, as illustrated in Figure 1:

(A) Isolated lines: Vertical lines were presented in isolation; observers judged the relative depth of the central pair.
(B) Closed object: Two horizontal lines connect the end points of the central vertical pair. The target lines are the same as in A, but now they form the vertical sides of a single, closed rectangle.
(C) Segmented objects: Each outer line pair was connected to create two closed rectangles. The central target lines now form the vertical sides of two discrete objects.

The stimulus was white (59.1 cd/m^2) on a mid-gray background (15.6 cd/m^2). Each line measured 3.3° × 0.1° and was laterally separated from its neighbor by 2°. The connecting horizontal lines had the same width (0.1°) and luminance as the vertical lines. Each closed object subtended 3.3° × 2.2°. The monocular image of the stimulus was symmetrical about the midpoint of the display both horizontally and vertically. When connected (Figure 1B, C), objects looked like slanted planar surfaces rotated about a vertical axis.

On each trial, one line of the central pair was presented at one of a range of crossed disparities (0°, 0.06°, 0.12°, 0.18°, 0.24°, and 0.3°). The other central line and the outer lines remained at the zero disparity; pilot testing ensured that all disparities were within Panum's fusional area. Binocular disparity was introduced by shifting each half image in opposite directions relative to the central fixation point.

Apparatus

Stimuli were generated using the Psychtoolbox package (Brainard, 1997; Pelli, 1997) for MATLAB on a Mac OS X computer. They were presented on a pair of LCD monitors (Dell U2412M, Dell, Austin, TX) in a mirror stereoscope arrangement at a viewing distance of 57 cm. The monitor resolution was 1920 × 1200 pixels with a refresh rate of 75 Hz. At this resolution and viewing distance, each pixel subtended 1.6 min of visual angle. The monitors were carefully calibrated and matched prior to testing and the gamma functions linearized. A chin rest stabilized head position during testing. Each observer's interocular distance was measured using a Richter digital pupil distance meter.

Depth estimates were made using a purpose-built touch sensitive sensor. A rectilinear SoftPot membrane potentiometer (SpectraSymbol) was mounted on a thin aluminum bar. The sensor strip was 200 mm long and 7 mm wide with a resistance of 10 kOhm. The potentiometer allowed linear measurements across the 200-mm length, with a resolution of approximately 0.2 mm. Responses were read using an analog to digital converter and a 16-bit micro controller. A rod at one end of the sensor was used to position the thumb, and its distance from the start of the sensor strip was adjusted prior to testing for each observer (this took into account differences in thumb thickness). The recorded voltage was converted to millimeters using a MATLAB script, and calibrated prior to testing.

Procedure

On each trial observers were asked to indicate the amount of depth they perceived between the two central test lines. To ensure that observers were not simply matching disparities in the stimulus (a task that reflects the precision of the disparity estimate, not the amount of depth perceived) we used a manual depth magnitude estimation task. They did this by positioning their thumb against the adjustable rest at the base of the sensor, and pressing the side of the nail of their

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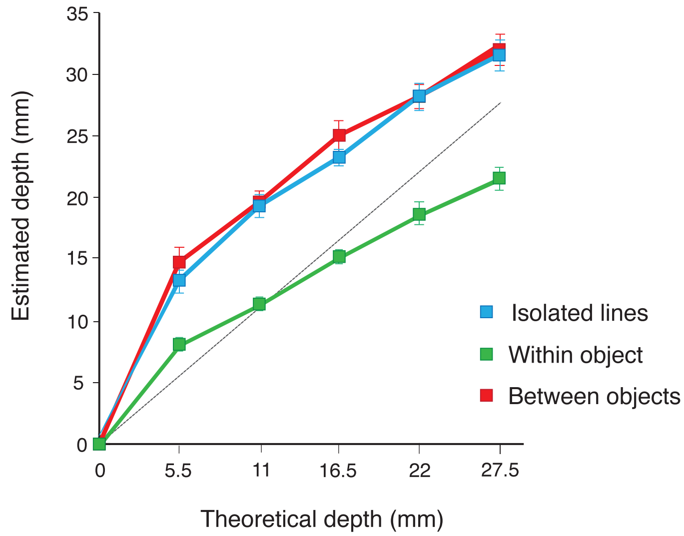

Figure 2. Perceived depth as a function of depth offset for three stimulus configurations: isolated lines (blue), closed object (green), and segmented objects (red). The abscissa shows the theoretical depth, and the ordinate shows the average depth estimated for 18 observers. Depth estimates are expressed as the equivalent theoretical disparity that would produce the depth at that viewing distance (see text). The dashed line indicates a gain of one and error bars show ± one standard error of the mean (at some points, the symbol size is larger than the error bar).

index finger at some point along the sensor to indicate depth magnitude. A small red LED positioned in front of the stereoscope mirrors, and 10.8° below the line of sight to the stimulus, illuminated when sufficient pressure was applied to the sensor strip. Observers were free to adjust their fingers until satisfied with their estimation. They then pressed the spacebar to record the response and move on to the next trial. Between trials, observers were asked to reposition their finger at the base of the sensor (the small LED was off when no pressure was applied to the strip). Viewing time was unrestricted and the experiment took place in a darkened room.

Prior to testing, observers completed a brief practice session of 30 trials to familiarize themselves with the depth estimation technique. The experiment consisted of 18 conditions (6 disparities × 3 configurations), with each condition presented 10 times in random order (5 left line and 5 right line). All 180 trials were completed in a single session. We validated the sensor measurement technique in a separate study in which observers estimated depth between a similar pair of vertical lines using three methods (in random order). In this yet-unpublished study we compared estimates made using the touch-sensor described here, thumb and index finger separation measured manually using a digital caliper and a virtual ruler displayed on a computer screen with an adjustable cursor. While the ease of measurement (and preferred method) varied across observers, we found that all inexperienced participants consistently overestimate the depth for the range of disparities used here regardless of the measurement method used.

Theoretical depth from disparity

To simplify comparison of on-screen theoretical depth to observers' estimated depth, we converted the stimulus disparities to theoretical depth in millimeters for each experiment. We used the conventional formula which relates disparity to predicted depth at a known viewing distance (57 cm): $Depth = (d * D^2 / IOD)$, where d is the relative disparity, D is the viewing distance and IOD is the interocular distance (see Howard, 2002, pp. 4–5). We used the average interocular difference for the observers that participated in each experiment. For Experiment 1, the theoretical depth between the two test lines corresponding to crossed disparities of 0°, 0.06°, 0.12°, 0.18°, 0.24°, and 0.3° were 0, 5.5, 11, 16.5, 22, and 27.5 mm respectively (with average IOD = 61.7 mm).

Results

Figure 2 shows the mean estimated depth for each condition as a function of the predicted separation in depth in millimeters. Because observers were told that some stimuli would have zero disparity, this response became stereotyped to the base of the sensor strip and had no associated variance. To avoid biasing the model fits, we excluded the zero-disparity estimates from analyses.

As shown in Figure 2, as the disparity between the target pair increased, estimated depth increased linearly in all conditions. However, there is a clear difference in the amount of depth perceived in the connected versus unconnected conditions. That is, when horizontal lines connected the target pair to form a closed object, the estimated depth was consistently reduced relative to the isolated lines condition. By comparison, depth percepts for the isolated lines and segmented objects conditions were very similar at all disparities and consistently enhanced relative to the closed object. This pattern of results was confirmed statistically. A repeated measures ANOVA showed main effects of Configuration, $F(1, 20) = 24.48$, $p < 0.0001$; $\eta^2 = 0.59$, and Disparity $F(1, 26) = 84.44$, $p < 0.0001$; $\eta^2 = 0.83$. There was no significant Configuration × Disparity interaction, $F(3, 54) = 1.96$, $p = 0.056$; $\eta^2 = 0.10$. Simple effects analyses were used to compare the differences among configurations. Contrasts revealed that perceived depth for the isolated lines, $F(1, 17) = 31.22$, $p < 0.0001$; $\eta^2 = 0.36$, and between objects, $F(1, 17) = 23.34$, $p < 0.0001$; $\eta^2 = 0.58$,

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conditions were significantly higher than for the closed objects. There was no difference between the results of the isolated lines and between objects conditions, $F(1, 17) = 0.34$, $p = 0.57$; $\eta^2 = 0.02$.

Discussion

Our results show that perceived depth from disparity is contingent on observers' figural interpretation of the stimulus. The amount of depth between two connected vertical lines is consistently and significantly less than those components in isolation. Thus, the contextual effects shown by McKee (1983) and others are not limited to threshold discrimination tasks, but also influence the perceived magnitude of the offset in depth between two suprathreshold disparity signals. While we did not explicitly assess grouping via amodal completion or common fate, it is likely that the observed effects on sensitivity reported by Yin et al. (2000), Liu et al. (1999), and Hou et al. (2006) are based on similar top-down influences. The effects of configural manipulation on perceived depth shown here are not due to local effects that are presumed to occur at early visual processing stages. This conclusion is supported by comparison of magnitude estimates in the within- and between- object conditions. In these cases, the local disparity information is identical, including the presence of L-junctions at the top and bottom of both target lines, but the amount of depth perceived is markedly different, and the between object condition results are virtually identical to those obtained in the isolated line configuration. Furthermore, our figural manipulations allow us to rule out explanations of this phenomenon based on disparity interactions from neighboring components, such as averaging or inhibition, or cue conflict with perspective. By extension, the similarity of the configuration in these two conditions also argues against an explanation based on the relative distance between salient features as suggested by Mitchison and Westheimer (1984). Instead we argue that, as in Kopfermann's (1930) study, the degradation of depth percepts shown here is a midlevel phenomenon based on figural grouping cues, in our case this depends specifically on perceived closure.

It is clear from these data that depth percepts are at a maximum when the depth judgment involves lines perceived to be either objects in their own right (isolated lines) or parts of two separate objects. On the other hand, depth estimates for these lines are consistently reduced when they form edges of a single closed object. It could be argued that depth estimates in the closed object conditions are closest to veridical, and that the data reflect enhanced depth percepts via segmentation for isolated objects. However, we found that our manual estimation technique yields constant depth overestimation for all observers at the disparity range tested here. These results suggest that it is more appropriate to focus instead on the differences between conditions, rather than the absolute amount of depth.

Experiment 2

A number of previous experiments have reported improved detection for targets that form part of a global figure. For example, Weisstein and Harris (1974) described object-superiority effects, whereby detection was more accurate when a target line was part of a global context with a three-dimensional appearance, than when presented in less structured, flatter configurations (see also Lanze, Weisstein & Harris, 1982; Purcell & Stewart, 1991). Subsequent work showed that the structural role of the target line was the critical factor in this phenomenon (McClelland & Miller, 1979). Contextual effects have also been documented in visual search tasks where detection is more rapid for closed stimuli than open contours (Elder & Zucker, 1993, 1994). Pomerantz and Portillo (2011) found that stimuli presented with additional contextual information (including connecting lines) are detected with more precision than the components in isolation (see also Pomerantz, Sager, & Stoever, 1977). On the other hand, visual search improves in a multi-element display when neighboring noise elements are grouped as a coherent Gestalt independent of the target (Banks & Prinzmetal, 1976; Banks & White, 1984). These results implicate feedback from midlevel processes that are involved in the recovery of global shape representation and implement well-known Gestalt grouping principles (Huberle & Karnath, 2012; Kubilius, Wagemans, & Op de Beeck, 2011; Peterhans & von der Heydt, 1989; Zhou, Friedman, & von der Heydt, 2000). Recent studies using 2D configurations have suggested that perceptual grouping based on Gestalt principles may be critical to the contextual modulation of Vernier acuity (Malania, Herzog, & Westheimer, 2007; Saarela, Sayim, Westheimer, & Herzog, 2009; Sayim, Westheimer, & Herzog, 2008, 2010). In the modern stereoscopic literature, however, the impact of Gestalt grouping on depth percepts has received relatively little empirical attention.

To date, there is no comprehensive explanation for these varied contextual effects. This is partly because even simple stimuli, like the line pairs used here, have multiple interpretations. With increased complexity it becomes difficult to determine which stimulus attribute drives the resulting percept. One approach to this problem is to systematically explore potential grouping cues by carefully changing one aspect of the stimulus at a time and assessing its impact on perception. This

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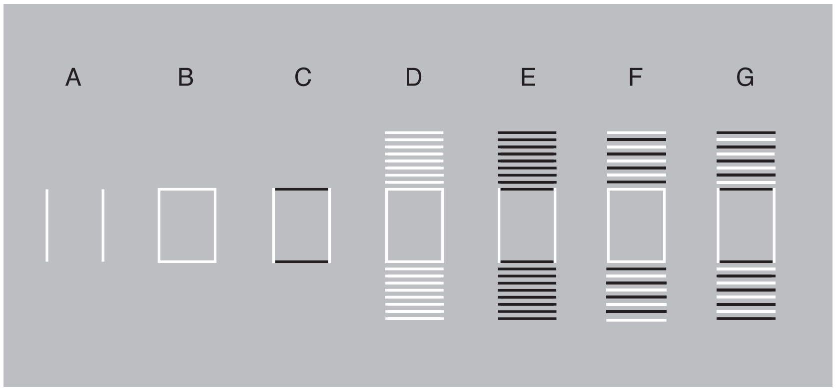

Figure 3. Stimuli used in Experiment 2. Note that we have shown the central lines only, the outer pair of vertical lines is not included in the Figure due to space considerations, but was present during testing as illustrated in Figure 1. Stimuli A and B are the isolated line and closed object stimuli used in Experiment 1, which were retested to aid comparison. In configurations C–G, grouping cues are varied, either in isolation or in combination, to influence perceived closure: (C) Reversed-contrast connectedness; (D) Uniform connectedness, proximity, similarity, and collinearity; (E) Reversed-contrast connectedness, proximity, similarity, and collinearity; (F) Uniform connectedness, proximity, and collinearity; and (G) Reversed-contrast connectedness, proximity; and collinearity.

approach has recently been used by Pomerantz and Portillo (2011) to study emergent properties of Gestalt grouping cues such as proximity and linearity. Using similar logic to investigate the influence of Gestalt cues on crowding, Westheimer, Herzog, and colleagues found that Vernier acuity depends on the "amount of grouping" in flanking lines introduced as crowding features (Manassi, Sayim, & Herzog, 2012; Malania, Herzog, & Westheimer, 2007; Saarela, Sayim, Westheimer, & Herzog, 2009; Sayim, Westheimer, & Herzog, 2008, 2010). For example, when a Vernier target (consisting of two equal-length vertical lines) was embedded in an array of flankers that had the same height and same color as the target, alignment thresholds were markedly poorer than when the Vernier target was presented on its own. However, this effect was reduced when grouping by similarity segmented the flanking lines from the Vernier target pair. These authors demonstrated that a number of classic Gestalt principles could help "ungroup" the disruptive flankers from the Vernier configuration, including similarity of color or contrast (Manassi et al., 2012; Sayim et al., 2008), and figural goodness (Manassi et al., 2012; Sayim et al., 2010). These experiments provide convincing evidence that 2D crowding cannot simply be explained by early, low-level interactions. In Experiment 2 we use a similar methodology to understand the role of grouping via closure in the third dimension.

In the terminology of perceptual organization, adding the horizontal connecting lines to the within-object condition in Experiment 1 introduces closure via element connectedness and similarity. In Experiment 2, we determine the extent to which perceived depth is modulated by perceived closure. To do this, we build on the configuration used in Experiment 1, but manipulate alternative grouping cues in the manner of Sayim et al. (2008) to evaluate their influence on perceived depth magnitude for these stimuli. To formalize the relationship between perceived closure and our stimulus manipulation we also asked a group of participants to rate the stimuli (shown in Figure 3) in terms of the "extent to which the central vertical lines were perceived as part of a closed object."

Methods

Observers

Nine participants from Experiment 1 took part in Experiment 2. Five of these were undergraduate students who, prior to the first experiment, had no previous experience with psychophysical tasks. The remaining four participants were experienced observers and one was an author. Apart from the author, none of the participants were aware of the experimental hypothesis or aims. Twenty people rated the stimuli used in Experiment 2 after it was completed (including the nine participants in the main experiment).

Apparatus and stimuli

The apparatus was the same as that described in Experiment 1. In addition to the original isolated line and closed object conditions from Experiment 1 (Figure 3A, B), we tested five configurations (Figure 3C–G) in which we manipulated Gestalt grouping cues related to proximity and similarity. The specific hypotheses are outlined below.

As shown in Figure 3C we reversed the polarity of the connecting lines (black = 3.1 cd/m^2), thereby removing the uniform properties of the elements forming the

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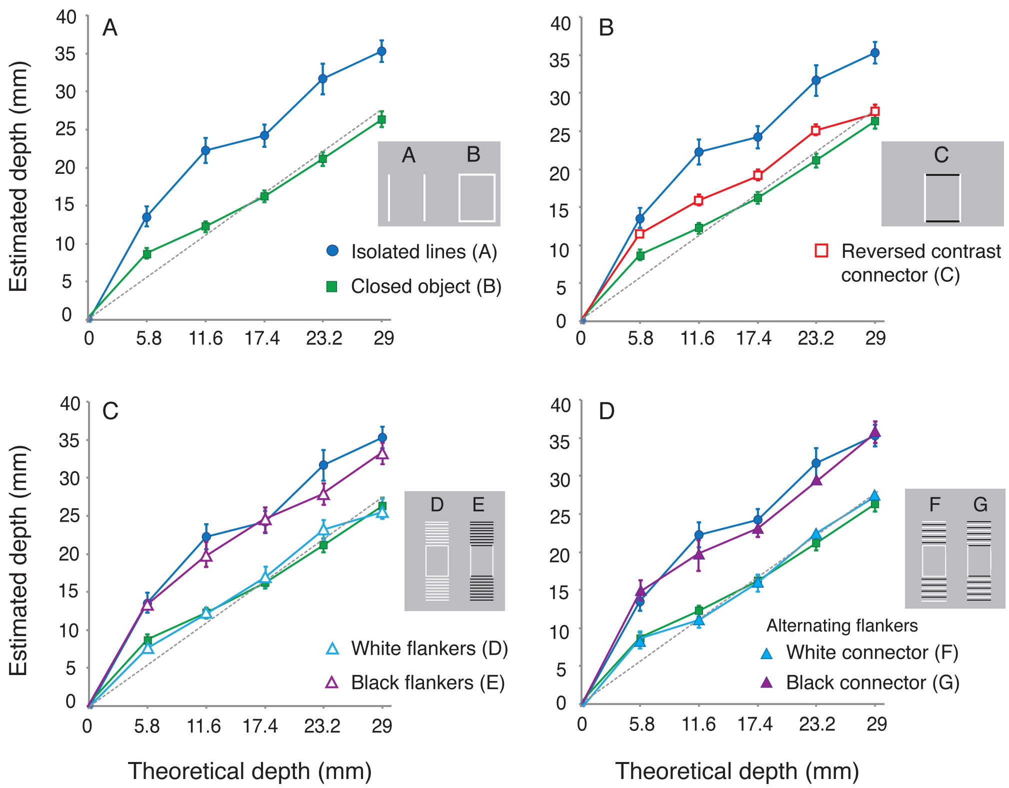

Figure 4. Perceived depth as a function of depth offset (in mm) for Experiment 2. In each Figure the abscissa shows the theoretical depth, and the ordinate shows the average estimated depth. The dashed line indicates a gain of one and error bars show ± one standard error of the mean. The stimuli are displayed to the right of the associated graphs where (A) Replication of Experiment 1 for isolated lines (circles) and closed objects (squares) for nine observers. For comparison, these data are replotted in subsequent Figures. (B) When the polarity of the horizontal connecting line was reversed. (C) Results for uniform flankers with the same contrast polarity as the horizontal connecting line. (D) Results for alternating contrast flanking lines extending from either white (positive contrast relative to vertical lines) or black (reversed contrast) connectors.

closed object to see if this alone would eliminate their disruptive influence. In the stimuli depicted in Figure 3D–G, the original closed object was flanked by equidistant horizontal lines, eight above and eight below the horizontal connecting lines. These flankers were added to provide alternative grouping solutions for the horizontal connectors, thus placing flanker/connector proximity and contrast similarity in competition with closure. All flankers had the same dimensions as the connecting horizontal lines (2.2° × 0.1°) and were separated from their nearest neighbors by 0.3°. The disparity gradient of the flankers matched that of the connecting lines on a given trial. There were four variants of the flanker stimuli. In the two uniform flanker configurations, all horizontal lines either had the same contrast as the vertical lines (Figure 3D) or had reversed contrast (Figure 3E). We also alternated the contrast of the flanking lines, starting from either the same (Figure 3F) or reversed polarity connecting line (Figure 3G). The seven configurations were randomly interleaved for a total of 420 trials (7 conditions × 6 disparities × 10 trials per condition) and were completed in two blocks within a single test session.

Procedure

Observers were asked to assess the amount of depth between the two central lines as described in Experiment 1, for the same set of crossed disparities (0°, 0.06°, 0.12°, 0.18°, 0.24°, and 0.3°). For this experiment, these disparities corresponded to theoretical depths of 0, 5.8, 11.6, 17.4, 23.2, and 29 mm (average IOD = 58.6 mm, for nine observers). To verify the effect of our grouping cue manipulation on the interpretation of the stimuli, we asked 20 observers to evaluate the extent to which the central vertical test pair appeared as part of a distinct object with 0 = not an object to 10 = a strong sense of an object. All observers were shown the stimuli in 2-D (on a sheet of paper) placed on a table under well-lit conditions.

Results and discussion

Perceived depth (in mm) for the isolated lines and closed object conditions in Experiment 2 are shown in Figure 4A; these data replicate the effects seen for these

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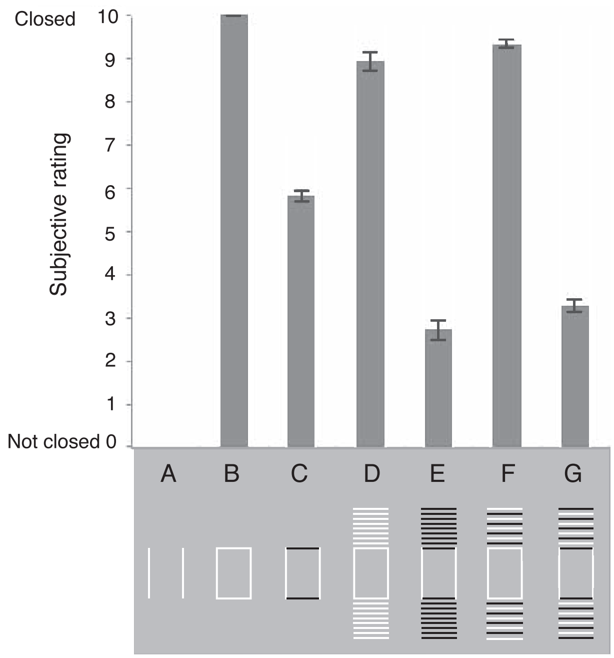

Figure 5. Subjective ratings for the seven stimulus configurations used in Experiment 2 (n = 20). Ratings range from 0 (not an object) to 10 (a strong sense of a closed object). The bar graph depicts the average rating for each of the stimuli (A–G). Error bars represent ± one standard error of the mean.

same conditions in Experiment 1 (Figure 2). Again, a repeated-measures ANOVA confirmed that the estimated depth between the vertical target lines in the closed object was much less than in the isolated vertical lines, $F(1, 8) = 8.68$, $p = 0.019$; $\eta^2 = 0.52$. The subjective ratings for these stimuli are shown in Figure 5 and confirm that the original closed object is consistently perceived as a closed object (rating = 10, $SD = 0$). These data are used for comparison with configurations C–G (Figure 3) in Figure 4 described below.

Grouping by closure: Uniform versus reversed contrast connectors

The simplest modification to the original stimulus configuration was reversal of the contrast polarity of the horizontal connecting lines as shown in Figure 3C. The depth estimates obtained for this stimulus are shown in Figure 4B. While this change to the stimulus slightly increased the magnitude of depth percepts relative to the closed object condition, the amount of depth remains less than that seen for isolated lines. A repeated-measures ANOVA confirmed that there is a significant effect of Configuration, $F(1, 9) = 8.43$, $p = 0.016$; $\eta^2 = 0.51$, and Disparity, $F(2, 18) = 104.28$, $p < 0.0001$; $\eta^2 = 0.93$. However, the Configuration × Disparity interaction is not significant, $F(4, 36) = 2.56$, $p = 0.077$; $\eta^2 = 0.24$. We used simple effects analyses to compare the differences among configurations. Contrasts revealed a significant difference between the isolated lines and reversed-contrast connector conditions, $F(1, 8) = 10.07$, $p = 0.013$; $\eta^2 = 0.58$. However, no significant difference was found between the conditions with reversed and uniform contrast connecting lines, $F(1, 8) = 4.24$, $p = 0.07$; $\eta^2 = 0.35$.

Subjective ratings for the reverse contrast lines configuration were in the mid-range of the scale (rating = 5.8, $SD = 1.1$), confirming that perceived closure was not as strong for this stimulus as found in the original (uniform contrast) closed object condition. The incomplete disruption of perceptual grouping reflected in these ratings is consistent with the fact that perceived depth remains at the level seen in the ungrouped configuration (though there is a trend towards an increase in perceived depth).

Alternative grouping solutions

While reversing the polarity of the connecting lines did not eliminate perceived closure, the rating data suggest that it was reduced (from 10 to 5.8). Similarly there was a trend towards an increase in perceived depth in that configuration. We added the flanking lines shown in (Figure 3D–G) above and below the horizontal connectors to provide an alternative grouping solution for the connecting lines to see if this would enhance the perceptual segmentation of the horizontal lines from the vertical target pair. We tested four versions of this configuration in which the horizontal lines had the same contrast polarity as the vertical lines (Figure 3D), reversed contrast polarity (Figure 3E), or alternating contrast polarity (Figure 3F, G).

We will first present the results obtained when all flanking lines had the same contrast polarity as the connecting lines, which were either the same as the vertical lines (Figure 3D) or had reversed polarity (Figure 3E). In these stimuli, proximity, similarity, and collinearity cues compete with closure of the central object. As shown in Figure 4C, it is clear that the amount of perceived depth depends critically on the relative contrast polarity of the horizontal lines. When the horizontal lines had the same contrast as the vertical lines, estimated depth was very similar to the uniform closed object at all test disparities. On the other hand, when the contrast of the horizontal lines was reversed, the amount of perceived depth increased to the levels reported for the isolated lines.

Statistical analyses confirmed these observations. There were significant main effects of both Configuration, $F(3, 24) = 4.77$, $p = 0.01$; $\eta^2 = 0.37$, and Disparity, $F(1, 15) = 99.74$, $p < 0.0001$; $\eta^2 = 0.92$, and no Configuration × Disparity interaction, $F(12, 96) = 1.31$, $p = 0.23$; $\eta^2 = 0.14$. Contrasts (using simple effects analyses) revealed that estimates for the same-contrast configuration was significantly different from the

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isolated lines, $F(1, 8) = 5.97$, $p = 0.04$; $\eta^2 = 0.43$, but were not different from the uniform closed object, $F(1, 8) = 0.02$, $p = 0.89$; $\eta^2 = 0.003$. On the other hand, estimates in the reversed contrast condition were not significantly different from the isolated lines, $F(1, 8) = 0.39$, $p = 0.55$; $\eta^2 = 0.05$, but were different from the uniform closed object, $F(1, 8) = 4.95$, $p = 0.05$; $\eta^2 = 0.43$.

These results show that the amount of perceived depth is modulated by the relative contrast polarity of the connecting line in the presence of an alternative grouping solution. That this is related to perceived closure of the central figure is confirmed by the rating data for these configurations. When the connectors are black (reverse polarity) and the flankers are black, closure ratings drop to 2.7 and perceived depth increases to that obtained when viewing isolated lines. However, when the connector is white (same polarity) the closed object ratings are high (9.1), and perceived depth returns to the level obtained when observers viewed the closed object configuration.

In configurations F and G in Figure 3 we controlled for contrast similarity in the flanking units to determine if proximity and collinearity would suffice to break the perceived closure. These conditions (along with the uniform same-polarity condition above) also serve as a control for the effects of simply adding more disparity information above and below the central figure. We measured depth estimates for the two-connector polarity conditions in the presence of alternating contrast flankers (Figure 3F, G). In both of these configurations the alternative grouping solutions for the horizontal connectors are still available via proximity and collinearity. The results (Figure 4D) are very similar to those shown in Figure 4C; in the presence of the alternative grouping solution (flankers) the contrast polarity of the connecting horizontal lines, relative to the vertical lines, determines the amount of perceived depth. As in Figure 4C, when the connectors are black (reverse polarity) depth percepts are virtually identical to those recorded for the isolated lines. When the connectors are white (same polarity) depth percepts follow those obtained in the closed object condition. Again, there were main effects of both Configuration, $F(2, 16) = 5.52$, $p = 0.015$; $\eta^2 = 0.41$, and Disparity, $F(4, 32) = 121.51$, $p < 0.0001$; $\eta^2 = 0.94$, and no Configuration × Disparity interaction, $F(12, 96) = 1.26$, $p = 0.26$; $\eta^2 = 0.14$. Contrasts with these alternating flanker conditions showed the same pattern of results as the uniform flankers described above. When the connector had the same contrast polarity as the vertical lines, depth estimates were significantly different from those obtained in the original isolated lines condition, $F(1, 8) = 6.95$, $p = 0.03$; $\eta^2 = 0.7$, but not different from the uniform closed object, $F(1, 8) = 0.06$, $p = 0.81$; $\eta^2 = 0.01$. On the other hand, when the contrast polarity of the connector was reversed, estimates were not statistically distinguishable from the isolated lines, $F(1, 8) = 8.68$, $p = 0.2$; $\eta^2 = 0.52$, but were different from the uniform closed object, $F(1, 8) = 5.81$, $p = 0.04$; $\eta^2 = 0.42$.

As was the case in the matched flankers conditions, we find that the depth percepts reported for the alternating polarity flanker conditions correspond well with the participants' closure ratings. Again, when the horizontal connector is white (same polarity) the depth percepts are low, and the closure ratings are high (9.3, Figure 5F). When the horizontal connector is black (reverse polarity) and perceived closure is weakened the depth percepts increase and the closure ratings drop to 3.2 (Figure 5G). From this, it is obvious that when combined with an alternative grouping solution, the similarity of the horizontal connecting lines to the vertical lines is the critical determinant of perceived closure and depth magnitude percepts.

The results of this experiment confirm that suprathreshold depth percepts for the vertical test pair are dependent on the perceived closure between the vertical test lines and the horizontal connecting lines. Without altering the configuration or spatial properties of the vertical lines, we were able to modulate their perceived separation in depth simply by changing the degree to which they were perceived as a part of a closed object. Importantly, these manipulations and their effects on suprathreshold depth percepts rule out explanations of this phenomenon based on early inhibition of neighboring components, cue conflict, the presence of local features (e.g., L-junctions) or their saliency.

General discussion

Our results show that perceptual organization, specifically figural grouping, modulates suprathreshold estimates of perceived depth. In Experiment 1 we demonstrate that the amount of depth estimated between a connected vertical line pair is markedly and consistently less than when these lines are presented in isolation. These results extend previous work using threshold measurements (McKee, 1983; Mitchison & Westheimer, 1984) and confirm that the figural interpretation of a stimulus influences perception of its 3-D form. Further, inclusion of our within- versus between- object comparison allows us to rule out explanations for the reduction in depth percepts that are based on local factors such as disparity averaging, inhibition, cue conflict, saliency, or other factors related to crowding. In Experiment 2, we demonstrate that the disruptive effect of connecting the central vertical line pair critically depends on the degree to which the target lines are perceived as part of a closed object. We manipulate perceived closure by adding classic grouping cues (proximity, similarity, and col-

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linearity), and validate this manipulation by asking observers to rate the degree of closure of the central target pair in all configurations.

The threshold-based literature on this topic (described in the Introduction) shows an increase in depth discrimination thresholds when a closed object is created or implied (McKee, 1983; Mitchison & Westheimer, 1984; Westheimer, 1979; Zalevski et al., 2007). In an earlier study, we replicated this finding using our modified version of McKee's stimulus (Deas & Wilcox, 2012). It is not obvious how the observed loss of precision at threshold maps onto the decreased depth magnitude percepts for clearly visible depth differences shown here. This is not surprising, given that many aspects of visual processing have different dependencies on stimulus attributes at and above threshold (for instance, contrast sensitivity as a function of spatial frequency).

Figural grouping and closure

The addition of horizontal connectors to the isolated line configuration changed the interpretation of the central (or outer) regions from isolated lines to parts of closed objects (confirmed by subjective reports shown in Figure 5). Gestalt psychologists at the beginning of the 20th century described the formation of shape with its inherent features (e.g., a rectangle with corners, internal angles) as an outcome of figural grouping according to Gestalt principles, which include closure (Koffka, 1935; Wertheimer, 1923/1967). Such closed structures were believed to be independent, stable organizations, which form a cohesive region compared to their surroundings (Koffka, 1935). In subsequent interpretations of Wertheimer's work, closure has been described as an emergent feature of the grouping process (Pomerantz et al., 1977; Pomerantz & Portillo, 2011; Treisman & Gormican, 1988; Treisman & Paterson, 1984), one that may be sufficient, but not necessary, for the perception of a global Gestalt (Wagemans et al., 2012). Alternatively, closure has been cast as a bridge between 1D contour and 2D form (Elder and Zucker, 1993). Judging from translations of Wertheimer's now famous 1923 paper (Ellis, 1967; Spillmann, 2012) and interpretations of the work by his contemporaries (Hartmann, 1935), Elder and Zucker's interpretation is most consistent with Wertheimer's views.

Elder and Zucker (1993) note that, in mathematical terms, closure is easily defined, as contours are either connected or not. Following Koffka's (1935) reasoning they point out that this is not the case for a perceptual description of closure, and there are many examples of configurations where edges are completed to form closed figures in the absence of spatial support (for example, the well-known Kanizsa figures). In a series of experiments, Elder and Zucker (1993) provide compelling evidence that closure represents a perceptual continuum, and that the presence of perceived closure is critical to the process of linking contours to shapes. While we have used a very different paradigm and focus on disparity processing, we believe that our results are also tightly tied to closure as an organizing principle.

Indeed, any manipulation that degraded perceived closure in our study caused an associated increase in perceived depth. For instance, closure was strongest when spatial properties of the connecting lines were most similar to the vertical lines (Figures 2 & 4A). However, by reversing the contrast polarity of the horizontal lines relative to the vertical test line, it was possible to reduce perceived closure (Figure 5C) and obtain slight enhancements in depth percepts (Figure 4B). When flanking lines were added near the horizontal connectors to provide an alternative grouping solution (via proximity, similarity, and collinearity) the perception of closure was markedly reduced and there was a concurrent increase in perceived depth (Figure 4C, D). The latter occurred, even though the horizontal elements were still physically connected to the vertical line segments. We note that in our stimuli similarity and element connectedness echo Palmer and Rock's (1994) uniform connectedness principle, but we do not propose that these attributes form entry-level units, nor do our data speak to this possibility.

It is tempting to posit a hierarchy of influence associated with the individual grouping cues used in our experiments. However, careful and considered efforts have been made to isolate and study the contribution of individual grouping principles (Banks & Prinzmetal, 1976; Elder & Zucker, 1993; Liu et al., 1999; Pomerantz et al., 1977; Pomerantz & Portillo, 2011) and it is clear that the influence and interaction of grouping principles is highly dependent on the configuration and the task demands. The current experiments were not designed to systematically evaluate this issue so the interested reader is directed to the work cited above. Here we highlight the role of perceptual closure and its interaction with other Gestalt grouping cues in determining the appearance of stereoscopic three-dimensional structure.

Grouping phenomena and slant in depth

We have established that Gestalt grouping is an important determinant of the perception of depth in simple figures. We argue that the addition of the horizontal line segments to the isolated line stimulus degrades depth percepts because the contours are transformed into objects via closure. However, this does not explain *why* perceived depth for closed objects is reduced relative to that seen in isolated line configurations. Research on the perception of slanted surfaces may

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provide some insight into this issue. The closed objects used here are slanted in depth, and it is well established that depth percepts for slanted surfaces with smooth disparity gradients are degraded (Gillam, 1968; Gillam, Flagg, & Finlay, 1984; Gillam & Ryan, 1992; Mamassian, 2008). Notably, slant judgments are still poor when perspective cues (foreshortening and convergence) are made consistent with the disparity offset (Ryan & Gillam, 1994). Further the degraded depth percepts can be observed when the slanted "object" is implied, for example, by contrast similarity (Mamassian, 2008) or good continuation (Fahle & Westheimer, 1988). Stevens and Brookes (1988) also found that relative depth percepts for two points were dramatically degraded when they were presented on a smooth disparity gradient, defined by either a line grid or a random dot surface. They argued that the disparity of the points is not computed directly when the points are seen as part of a surface, instead the depth is computed relative to that surface. This result was extended by Glennerster and McKee (1999) using sparse dots and interpolated surfaces. We suggest that the disruption of disparity processing described by Gillam, Stevens, and others reflects a common property of the stereoscopic system which applies smoothing operations to binocular disparity (as proposed by Marr & Poggio, 1976, 1979) in the absence of boundaries defined by depth discontinuities within coherent surfaces or closed objects. Note that this disruptive phenomenon is not simply tied to the presence of a disparity gradient between features; it does not occur when a disparity gradient is present between isolated stimuli. Instead, reports of degraded depth percepts for slanted stimuli are only obtained when there is some spatial support for interpretation of the two features as a single object. In most instances in the literature this support is explicit, as closed rectangular grids, frames, or random dot surfaces are used as stimuli (Gillam et al., 1984; Stevens & Brookes, 1988). The role of perceptual closure, and therefore Gestalt grouping, in mediating the observed underestimation of stereoscopic slant has been underappreciated. Our experiments suggest that these phenomena share a common cause: within object disparity smoothing operations that rely on perceptual grouping and serve to enhance object cohesion.

Keywords: stereopsis, depth, perceptual grouping, Gestalt grouping, depth magnitude, quantitative depth, segmentation

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