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# Effect of disparity on the perception of motion-defined contours

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## Abstract

We present three experiments that explored the effect of binocular disparity on the perception of contours defined by motion in a Spatiotemporal Boundary Formation. Depending on the disparity, the stimulus is perceived as an object that moves behind a holed surface (occluded configuration) or as a luminous transparency that moves over a surface that contains dots (occluding configuration). In all of the experiments, we used a Vernier task to assess the strength of contour perception. In the first experiment, we measured acuity as a function of disparity for a range of speeds and dot densities. The results showed that, despite the difference in the percepts, acuity was similar in both situations, replicating the dependence on speed and dot density demonstrated in previous studies. In the second experiment, the results showed that the dynamics of contour integration were identical for both occluded and occluding configurations. In the third experiment, we tested whether the mechanism of contour integration works independently from the interpretation of the scene. In this experiment, we inverted the disparity during stimulus presentation so that the stimulus switched between occluded and occluding configurations. The results showed that the switch of the depth order increased the threshold to the value obtained with a shorter presentation time. This might be produced by a resetting of the integration process driven by the change of depth order. The results are discussed within a conceptual model that places the process of contour integration in the context of the perception of objects in a Spatiotemporal Boundary Formation.

**Keywords:** spatiotemporal boundary formation, contour completion, Vernier acuity.

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## 1. Introduction

In real life, the human visual system continuously faces difficulty with obtaining information about objects of interest from the visual scene. Such information is often incomplete and spatially or temporally fragmented because of, for example, occlusions (Gibson, Kaplan, Reynolds, & Wheeler, 1969; Gibson 1979). However, the visual system is highly efficient in performing contour completion in an automatic and apparently effortless way (Shipley & Cunningham, 2001). Such filling-in of missing contour information sometimes leads to percepts of illusory contours, as in the Kanizsa Triangle (Kanizsa, 1979).

Contour completion can occur in both static and dynamic situations, but motion becomes critical for this task in some cases (Anderson & Barth, 1999; Nawrot, Shannon, & Rizzo, 1996; Regan, 1986; Shipley & Kellman, 1997; Sinha, 2001). For example, when there is relative movement between two surfaces and one of these surfaces occludes the other, the patterns of accretion or deletion that appear in this situation may contain a large amount of information about the shape of the objects (Gibson, 1979). Let us imagine a real-world situation where an animal that stays static behind a bush formation (occluder) may remain "invisible" until it moves. When it moves, the free spaces in the bushes reveal different fragments of the animal that the brain can put together thanks to a mechanism of spatiotemporal integration. Even when the brain has access to a limited amount of information about the object contours at each moment, movement may supply the information needed by the system to complete the missing fragments (Nawrot et al., 1996). A typical stimulus that is used to study cases in which objects are fragmented because of spatiotemporal occlusions consists of a random-dot array, in which a fictitious test region (i.e., a mathematically defined region, named pseudosurface by Shipley & Kellman, 1994) is defined by changing the color (or luminance, depending on whether the stimulus includes chromaticity) of the dots that fall on such a region (Andersen & Cortese, 1989; Bruno & Bertamini, 1990; Bruno & Gerbino, 1991; Cicerone & Hoffman, 1997; Cicerone, Hoffman, Gowdy, & Kim, 1995; Cunningham, Shipley & Kellman, 1998a, b; Shipley & Kellman, 1994, 1997). Because the dots remain static,

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when the test region moves, the dots change color as the region reaches or leaves them. The pattern of correlated dot color transitions reveals the boundaries and shape of the region and produces the perception of apparent movement of the test region (Spatiotemporal Boundary Formation [SBF]; Shipley & Kellman, 1997; movie demos can be found in Barraza & Chen, 2006; Figure 1).

Interestingly, this stimulus supports two different perceptual interpretations (i.e., different appearances; Chen & Cicerone, 2002a). Sometimes the test region is interpreted as an object that moves behind a surface that contains holes through which the moving object is seen (i.e., occluded object situation; Barraza & Chen, 2006), and sometimes luminous transparency is perceived that moves in front of the gray patch. In the second case, the transitions of the dot colors produce color spreading on the gray patch, revealing the object boundaries (i.e., illusory contours; Cicerone et al., 1995; Cicerone & Hoffman, 1997). Despite the evident differences in the percepts, unclear is whether the sharpness of the contours is functionally similar (i.e., whether psychophysical performance in tasks that depend on contours sharpness is similar in these two situations). In a previous study, Barraza and Chen (2006) obliquely dealt with this problem without giving a conclusive answer. The authors performed a series of experiments in which they analyzed the effect of adding physical contours to an SBF stimulus on performance in a Vernier acuity task. In their main experiment, the observers had to report the misalignment of two motion-defined bars that moved horizontally in two situations: (*i*) two luminance-defined flankers located adjacent to the SBF stimulus moved at the same speed as the bars, in which they were visible (i.e., not occluded) parts of these bars and (*ii*) the classic SBF stimulus was displayed without the flankers. In these displays, the flankers strongly bias perception toward the occluded object situation because these flankers seem to belong to the same object as the motion-defined bars. The authors found that the presence of the flankers increased Vernier acuity compared with the SBF stimulus without flankers. Although the presence of flankers appears to disambiguate the appearance of the stimulus, the effect cannot be attributed only to this factor because an increase in acuity can be explained by a facilitatory effect of the flankers on the integration of contours along the motion-defined bar, which might improve its visibility (Cass & Spehar, 2005; Field, Hayes, & Hess, 1993; Polat, 1999; Polat, Mizobe, Pettet, Kasamatsu, & Norcia, 1998; Polat & Sagi, 1993; Solomon & Morgan, 2000).

To gain deeper insights into the mechanisms involved in the perception of contours in an SBF, we devised a series of experiments to evaluate the performance of human subjects in a task that depends on the sharpness of the contours by considering two perceptual interpretations of the stimulus. We adopted a Vernier task and measured acuity to assess contour sharpness. Vernier acuity is well known to be directly related to target visibility (Carney, Silverstein, & Klein, 1995; Waugh & Levi, 1993; Westheimer & Pettet, 1990). We assume that we can assess the visibility of the contours by measuring Vernier acuity. Therefore, we can rely on the accumulated knowledge provided by studies of Vernier acuity as a reference to analyze our results. To disambiguate the two perceptual interpretations, we added binocular disparity to the classic SBF stimuli. In the first experiment, we measured Vernier thresholds as a function of disparity (including positive and negative values) for a range of speeds and dot densities. We investigated whether disparity affects performance and the mechanisms of spatiotemporal integration. In the second experiment, we investigated whether the time course of Vernier acuity for both perceptual interpretations follows the typical asymptotic decrease in Vernier acuity measured with luminance-defined stimuli. Finally, we investigated whether the mechanism of contour integration accumulates the information collected during a time lapse during which a change in perceptual interpretation occurs (i.e., inversion of disparity). This last experiment tested whether the information used for contour completion is used independently of the perceived depth order (front/back).

The results are discussed within a conceptual model that frames the process of contour integration within the context of the perception of objects in the SBF.

## 2. Experiment 1: Effect of Disparity on Contour Sharpness

### *2.1. Methods*

2.1.1. Observers

Five observers participated in this experiment. Observer JGCH is one of the authors, and the other four observers were naive to the purpose of this experiment. Observers MAK and PD had corrected vision to 20/20, and JGCH, MD, and IC had normal vision. The average age across observers was 28.8 ± 2.8 years. All of the observers were paid for their participation in the experiment.

2.1.2. Apparatus

The stimuli were displayed on two 19” cathode-ray-tube monitors using MATLAB software with the Psychophysics Toolbox (Brainard, 1997) and Video Toolbox (Pelli, 1997). Gamma calibration was performed with a Minolta LS-110 luminance meter.

During the sessions, the participants were seated, and their heads were immobilized with a chin rest. The room was completely dark, with the exception of illumination provided by the monitors.

2.1.3. Stimuli

The stimulus consisted of a square gray patch that contained a quasi-random dot pattern in which the dots remained static during the stimulus presentation. To avoid dot clusters, we divided the patch into 16 portions and spread 1/16 of the dots randomly in each portion.

The size of the gray patch was 5 × 5 deg, and its background luminance was 19 cd/m². The gray patch was presented against a black background of 0.1 cd/m² that extended across the entire monitor. Dot luminance was modulated to define two rectangular test regions. Dots located within the test regions (white dots) had a luminance of 38 cd/m², and the others (black dots) had a luminance of 0.1 cd/m². The width of the test regions was 1 deg, and the dots had a size of 4 arcmin. This size was defined after performing preliminary tests and verifying that this combination optimized the perception of test bars and edges. The top and bottom parts of the test region were half of the patch height and extended from the center toward the top and bottom margins of the patch (see a frame in Figure 1).

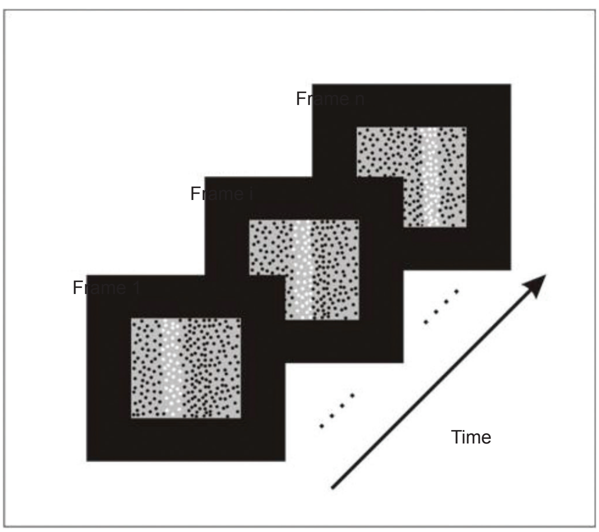


**Figure 1.** Scheme of the dynamics of stimulus presentation. The figure shows three frames in which one can see how the test region (white dots) is displaced in time. Notice that the position of the dots is identical in the three frames. This is because the dots do not move but change their color when they become part of the test region.

To produce apparent movement of the test region, the luminance of the dots changed when the leading or following borders of the region reached each dot. The exact time of the luminance change corresponded to the moment at which the border coincided with the center of the dot. This produced an error of ± ½ dot size. Notice that no edges could appear inside the dots. Figure 1 schematically shows the dynamics of the stimulus presentation. These three frames show how the test region was displaced in time.

The test region was translated at three speeds (1, 2, and 4 deg/s), and speed was one of the independent variables of the experiment. We adopted these speeds because most changes in thresholds are produced within this range (Andersen & Cortese, 1989; Barraza & Chen, 2006). The experiment was performed for two values of dot density (4 and 8 dots/deg$^2$), and the stimulus duration was 350 ms.

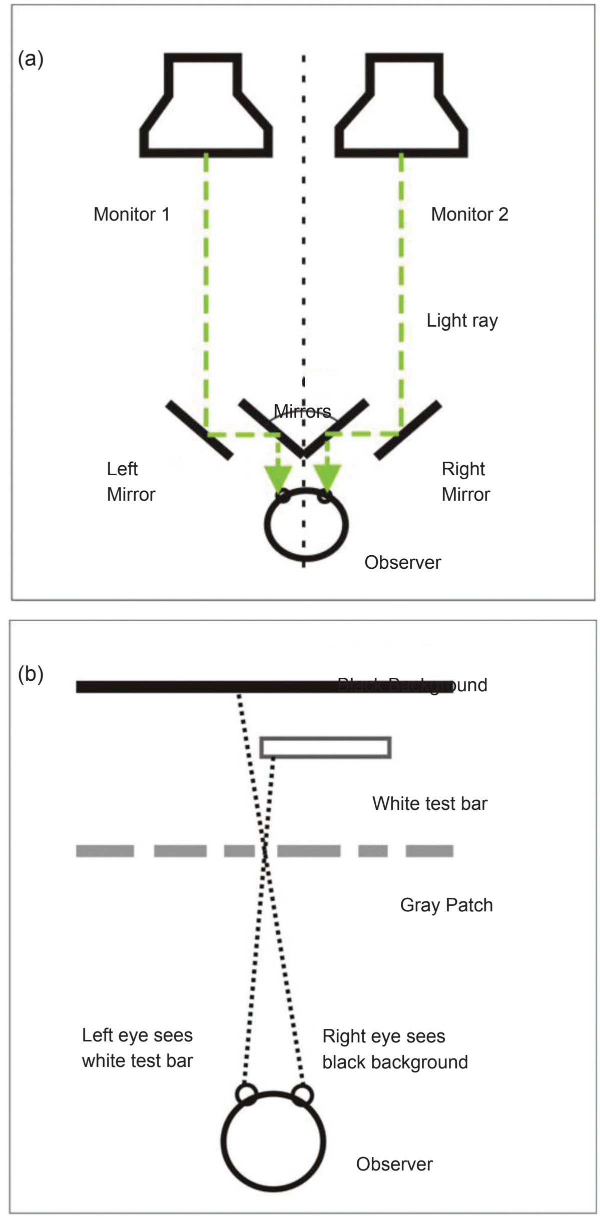


**Figure 2.** (a) Schematic of the stereoscope used in this experiment. Three-dimensional movies were created by displaying the disparate images for each eye on two different monitors and taking them to the observer through two paths of mirrors. (b) This picture illustrates the way we created disparity using pictorial cues. The dots located near the boundaries of the test region may be colored differently, depending on whether the background (black) or test region (white) is seen through the aperture from the point of view of each eye. What we displace in one image with respect to the other image to produce disparity is the position of the test region, which defines the color of the dots. For example, a displacement of the test region on Monitor 2 to the right with respect to the one displayed on Monitor 1 produces the perception of a white bar that moves behind the gray patch (occluded object situation).

Binocular disparity was produced using pictorial cues (Chen & Cicerone, 2002a,b; Nakayama & Shimojo, 1990). In this case, slightly different images were displayed to each eye using a stereoscope (Wheatstone, 1838; Figure 2a). Figure 2b shows a scheme that illustrates how we produced these images. The dots located near the boundaries of the test region may have different luminance, depending on whether the background (black) or test region (white) is seen through the aperture from the point of view of each eye. In other words, what we displaced in an image with respect to the other image to produce disparity was the position of the test region, which defined the luminance of the dots. Displacement of the test region to the right on Monitor 2 with respect to the region displayed on Monitor 1 produced the perception of a white bar that moved behind the gray patch (i.e., occluded object situation). When the test region was displaced to the left on Monitor 2, luminous transparency with well-defined illusory contours (i.e., modal perception), namely lightness that spread over the patch, could be perceived (Chen & Cicerone, 2002a). The displacement of the test region was calculated using the formula for binocular disparity according to geometric constraints.

$$\alpha = \frac{d_p z}{D + z}$$

α is the displacement of the test region in corresponding points between both images in centimeters. *dp* is the interpupilar distance in centimeters. *z* is the depth difference between the patch and test region in centimeters. *D* is the observation distance in centimeters. This displacement can be converted to a visual angle to express the disparity used in the experiment (+161, +54, 0, -55, and -168 arcsec). Disparity was another independent variable in this experiment. The small asymmetry in the range of disparity is caused by these values being derived from depth difference values (+3, +1, 0, -1, and -3 cm). Additionally, the test region width was slightly modified to compensate for the size distortions caused by size constancy.

Because some corresponding dots appear with different luminance on each eye, binocular rivalry is produced for situations in which speed = 0 deg/s, so only the luminance of the dominant eye is perceived (Chen & Cicerone, 2002b). The effect is almost not perceived for speed = 1 deg/s and disappears for speed = 2 deg/s.

2.1.4. Procedure

A Vernier configuration was designed by introducing an offset between the lower and upper parts of the test region. We instructed the subjects to attend to the leading contour of the test region that would appear near and across the center of the screen and respond by clicking a mouse button if the lower edge was to the left or right of the upper edge. The test bar moved horizontally, and its direction was randomized across trials.

The observer started each block of trials by clicking a mouse button. After the stimulus was presented for 350 ms, a uniform gray patch was displayed while waiting for the observer's response. Once the observer responded, the system informed the observer with a beep whether his or her response was correct or incorrect and started the next trial automatically after 100 ms.

We used a forced-choice paradigm with the method of constant stimuli to obtain the subjects' psychometric functions. To obtain these functions, a set of six stimuli was used in each block of trials. The number of conditions we tested in this experiment was 30 (3 speeds × 2 densities × 5 disparities). Each threshold was obtained from 360 trials, which were performed in three blocks of 20 repetitions each. The experiment was performed in 9 sessions, in which all of the experimental conditions were randomized.

2.1.5. Data analysis

Vernier thresholds at 82% performance were obtained by fitting Weibull functions to the data. To carry out the fittings, we used Psignifit 2.5.6 software, which implements a maximum likelihood method and provides confidence intervals using bootstrap methods (Wichmann & Hill, 2001a,b).

### *2.2. Results*

We measured Vernier thresholds as a function of disparity (+161, +54, 0, -55, and -168 arcsec) for three speeds (1, 2, and 4 deg/s) and two dot densities (4 and 8 dots/deg$^2$).

Figure 3 shows the average threshold among observers as a function of disparity for both dot densities (panel a: speed = 1 deg/s; panel b: speed = 2 deg/s; panel c: speed = 4 deg/s). We added trend lines to all of the sets of data to analyze the effect of disparity on Vernier thresholds. These lines show that the slopes were close to zero for all of the experimental conditions. This means there was not a systematic effect of disparity on performance for these conditions. We performed a *t*-test for each experimental situation and observer, showing that only two of 30 lines presented slopes that were different from zero (observer JGCH: speed = 1 deg/s, density = 8 dots/deg$^2$, $t = -3.88$, $p = .030$; observer PD: speed = 1 deg/s, density = 8 dots/deg$^2$, $t = -4.44$, $p = .021$), and only one that was marginally equal to zero (observer MAK: speed = 4 deg/s, density = 8 dots/deg$^2$, $t = -3.12$, $p = .053$). To avoid inflation of significance by multiple testing, sequential Bonferroni correction was applied (Holm, 1979).

Figure 4 shows the same set of data plotted as a function of speed and sign of disparity (panel a: dot density = 4 dots/deg$^2$; panel b: dot density = 8 dots/deg$^2$). In each panel, we compared the results obtained without disparity against those obtained with two opposite values of disparity. The figure shows the typical decrease in threshold with increasing speed (Andersen & Cortese, 1989; Barraza & Chen, 2006), revealing a spatiotemporal integration mechanism. This mechanism

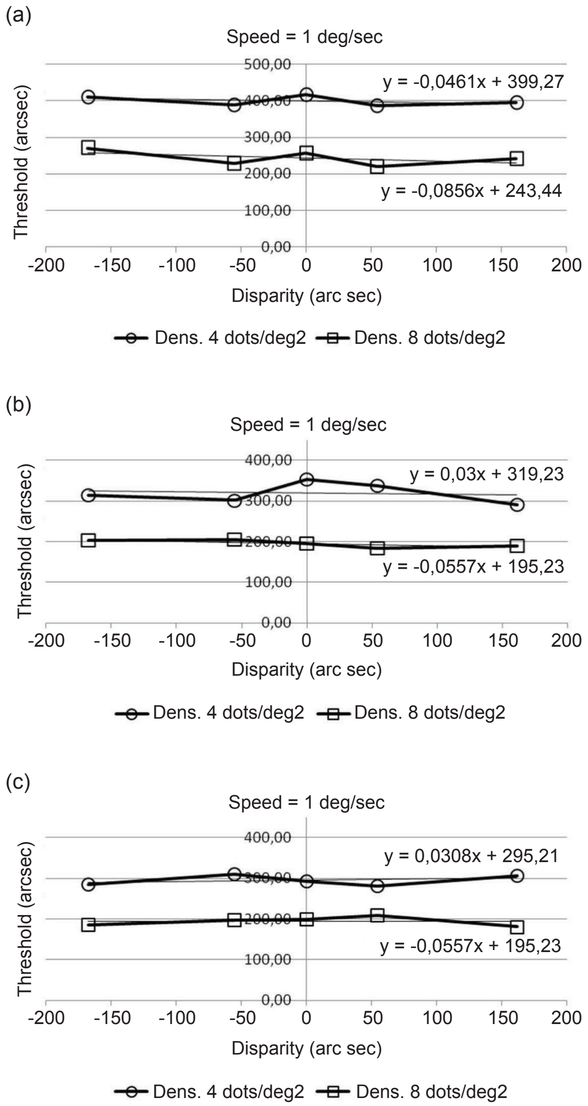


**Figure 3.** Vernier threshold as a function of disparity. The data correspond to the average thresholds among observers for dot densities of 4 and 8 dots/deg$^2$. Different panels show the results for speeds of (a) 1, (b) 2, and (c) 4 deg/s.

does not appear to depend on whether disparity is positive or negative because the curves were all similar. Interestingly, for the lower density, the thresholds for disparities that were different from zero were lower than the thresholds for zero disparity. Disparity appeared to help the observer perform the psychophysical task by disambiguating the stimulus. For the higher density, the thresholds fell to approximately half of the above values, and the effect appeared to disappear.

## 3. Experiment 2: Time Course of Integration

The integration of contours in the SBF was hypothesized to occur within a time window. The system should collect sufficient information during that time to reconstruct the contour. If the stimulus is displayed for a shorter period of time than the time needed for the process, then integration is incomplete, reflected by higher thresholds caused by the reduced visibility of the contour (Palmer, Kellman, & Shipley, 2006). In this experiment we tested whether the time course of contour integration depends on whether the contour is in an occluded or occluding configuration. We generated these configurations by adding disparity to the stimuli.

### *3.1. Methods*

3.1.1. Observers

Eight observers participated in this experiment. One of the authors (JGCH) and MAK also participated in Experiment 1. All of the observers had normal or corrected to 20/20 vision. All of the observers were paid for their participation in this experiment. The average age across observers was 28.3 ± 2.5 years.

3.1.2. Stimuli

The stimulus and task remained the same as in Experiment 1. Only one density (8 dots/deg$^2$) and one speed (4 deg/s) were tested for disparities of +161 and -168 arcsec.

### *3.2. Results*

Figure 5 shows the average thresholds among observers for both disparities as a function of presentation time (50, 100, and 350 ms). The plot shows the typical

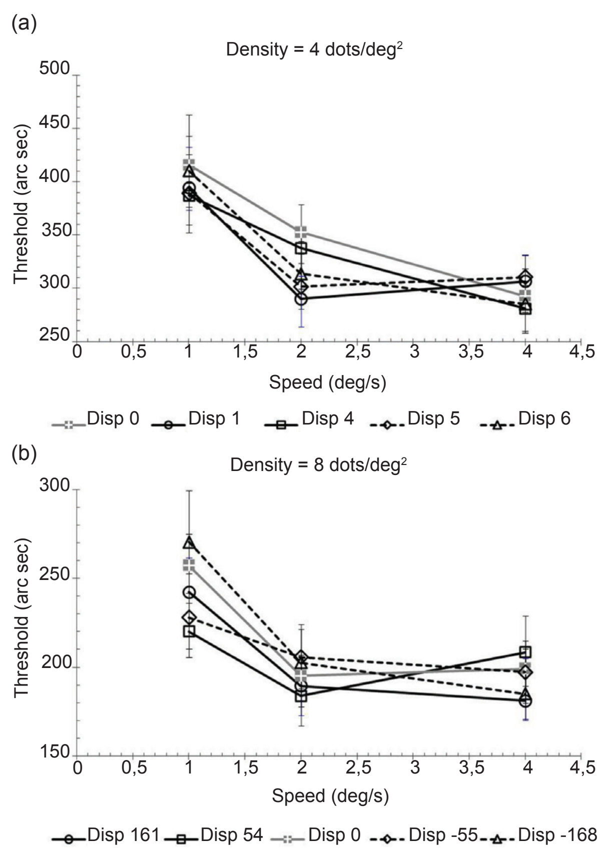


**Figure 4.** Vernier threshold as a function of speed. The data correspond to the average thresholds among observers. The two panels show the data that correspond to disparities of 0, ±1, and ±3, respectively. The different panels show the results for different dot densities: (a) 4 dot/deg$^2$ and (b) 8 dot/deg$^2$.

asymptotic decrease in Vernier threshold over time in which the visibility of the contours increased with the stimulus duration (Foley & Tyler, 1976; Sun & Lee, 2004). This is consistent with the hypothesis that contour completion in the SBF is mediated by an integrative mechanism. The results showed no effect of disparity on the time course of contour integration. The statistical analysis of the data showed that only one of the eight observers exhibited (for the 100 ms presentation time) a significant difference between the results obtained with opposite values of disparity.

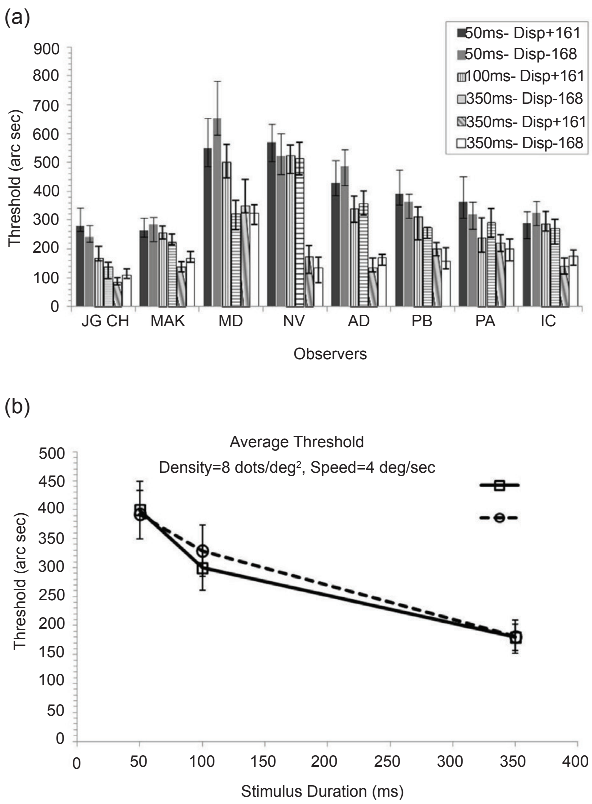


**Figure 5.** Vernier threshold as a function of stimulus presentation time for positive and negative disparity. (a) Individual results for the eight observers. (b) Average results.

## 4. Experiment 3: Effect of Change in Depth Order during Temporal Integration

At this stage, we showed that psychophysical performance in a Vernier acuity task for motion-defined contours in occluded and occluding configurations was similar. Moreover, we showed that the integrative mechanism involved in contour completion and its dynamics is similar for both situations. In Experiment 3, we investigated whether the mechanism of contour integration accumulates the information collected during a time lapse during which a change in depth order occurs. We know that depth order is critical for the representation of object unity (e.g., Kellman, Guttman, & Wickens, 2001). A change in depth order may be imputed, quite possibly, to the presence of a new object. Particularly in the case of the SBF, occluded and occluding configurations generate different percepts associated with different scene interpretations. Therefore, a reasonable hypothesis is that the mechanism of contour integration does not cumulate the information that comes from contours with opposite depth orders. Instead, depth order would produce a restart of the mechanism of contour integration. If so, then performance might decrease as the stimulus duration is shortened.

### *4.1. Methods*

4.1.1. Observers

Three observers participated in this experiment: one of the authors (JGCH) and two other participants who were naive to the purpose of the experiment. All of the observers had normal or corrected to normal vision. The observers were paid for their participation in this experiment. The average age across observers was 27.8 ± 3.9 years.

4.1.2. Stimuli

The stimulus was a modified version of the stimulus used in the previous experiments. The dots were now distributed over two contiguous patches with different luminance, in which the left patch was gray and the right patch was white (Figure 6). In this experiment, the test region was also defined with white dots. We used three stimulus configurations in this experiment. Depending on the configuration, the gray and white patches could be assigned disparities such that both were closer than the test region (occluded configuration), both were further than the test region (occluding configuration), or the gray patch was in front and the white patch was behind the test region, forming a kind of depth step between the two surfaces. The test region could move from left to right or from

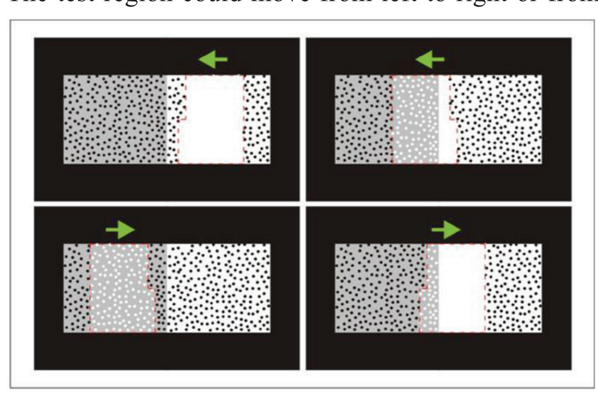

**Figure 6.** Examples of the stimulus used to measure the effect of changing the depth order during stimulus presentation on Vernier threshold. In this experiment, only one of the contours contained the misalignment (signal). The top-left picture represents the case in which the test region moved to the left, and the signal was in the leading contour. The top-right picture illustrates the case in which the stimulus moved to the left, and the signal was contained in the following contour. The lower pictures correspond to the cases in which the signal was contained in both the leading and following contours for rightward motion.

right to left, producing a transition from an occluded to occluding configuration (and *vice versa*) in the third configuration described above. In this experiment, the offset for the Vernier task was only introduced on the leading contour of the test region because the stimulus could not be set in a way that both contours appeared half of the time on the gray patch and half of the time on the white patch as the experimental design required. The size of each patch was 3.5 deg (width) × 3 deg (height). The gray patch had a luminance of 19 cd/m$^2$, and the white patch had a luminance of 38 cd/m$^2$. As in the previous experiments, the luminances of the black and white dots were 0.1 and 38 cd/m$^2$, respectively. The size of the test regions was 1.5 deg (width) × 1.5 deg (height). The bottom test region was stretched or shrunk to produce the offset for the Vernier task. The disparity added to this region was 4.42 arcmin.

4.1.3. Procedure

Three conditions were tested in this experiment: occluded (A), occluding (B), and occluded plus occluding (A+B). In the A+B condition, the test region appeared half of the time behind the gray patch and half of the time in front of the white patch, producing a transition between these two situations. The three conditions were tested for three presentation times: 100, 200, and 400 ms. Similar to the previous experiments, the observer started each block of trials by clicking a mouse button. After the stimulus presentation, a uniform gray patch was displayed while waiting for the observer's response. Once the observer responded, the system informed him or her whether the response was correct or incorrect and started the next trial automatically after 100 ms. The observer's task was to indicate whether the lower part of the test region was wider or thinner than the upper part of the test region. We used a forced-choice paradigm with the method of constant stimuli to obtain the subjects' psychometric functions. To obtain these functions, a set of six stimuli was used in each block of trials. As in the previous experiments, each Vernier threshold was obtained from three blocks of 120 trials (20 per stimulus).

### *4.2. Results*

Figure 7 shows the Vernier thresholds for the three stimulus durations and conditions for the three observers. For all of the stimulus durations, Vernier thresholds for the A+B condition were higher than those for the A and B conditions that, in turn, were similar to each other. What can this difference be attributed to? The stimuli for the three conditions were identical except for disparity. This suggests that the depth step produced the increase in thresholds. Notice that the threshold for 200 ms obtained in condition A+B was similar to the thresholds obtained for 100 ms in conditions A and B. Moreover, the threshold for 400 ms obtained in condition A+B was similar to the thresholds obtained for 200 ms in conditions A and B. This might indicate that the effective stimulus duration in condition A+B was shorter (perhaps by half) than in conditions A and B. One possible explanation for this result is that the change in the percept produced by the depth step in condition A+B reset the process of

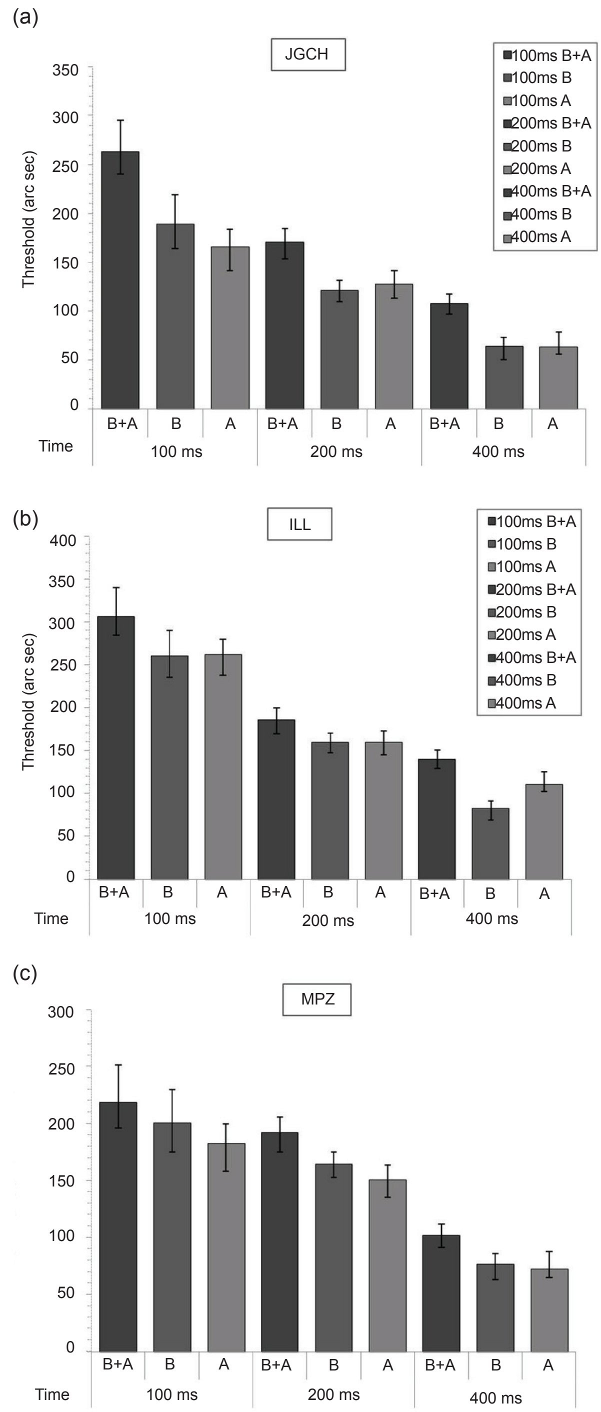


**Figure 7.** Vernier threshold as a function of stimulus presentation time for the three experimental conditions: A (occluded), B (occluding), and A+B (occluded plus occluding). In the A+B condition, the test region appeared half of the time behind the gray patch and half of the time in front of the white patch, producing a transition between these two situations. Each panel corresponds to the data of one observer.

contour integration, which may result in a shortening of the effective stimulus duration.

## 5. Discussion

We present a series of experiments that explored the perception of motion-defined contours in occluded and occluding configurations using a stimulus known as the SBF (Shipley & Kellman, 1997) and introducing disparity to create the two-type configurations. In the first experiment, we measured Vernier thresholds as a function of disparity for a variety of experimental conditions, including variations in speed and dot density. We found no dependence of performance on disparity for any of the conditions. This means that contour sharpness, measured through Vernier acuity, does not depend on whether the stimulus is interpreted as an occluded object seen through apertures in the patch or as a luminous transparency that moves over a textured surface. We also showed that the typical increase in acuity with speed, describing the spatiotemporal mechanism of contour integration, was unaffected by disparity (Andersen & Cortese, 1989; Bruno & Bertamini, 1990; Barraza & Chen, 2006). In the second experiment, we measured Vernier acuity as a function of presentation time and found no differences between the results obtained with either configuration for any of the presentation times. This suggests that the dynamics of contour integration are identical in both situations. In the third experiment, we investigated whether a change in depth order during stimulus presentation affects contour integration. The results of this experiment showed that the switch of depth order increased the threshold to a value obtained with a shorter presentation time, leading to the conclusion that a change in depth order during stimulus presentation resets the process of contour integration, resulting in a shortening of the effective stimulus duration.

To discuss these results, we propose to analyze what we see when we watch an SBF stimulus and only then to set the process of contour integration within the context of a conceptual model for object perception.

### *5.1. What do we see in a SBF stimulus?*

Many of us have experienced objects that cannot be distinguished from their surroundings when stationary but become quite visible when moving. In an SBF, motion can reveal the boundaries of an object even though the physical contours are never visible and the object is only defined by the change of the dot color or luminance (movie demos can be found in Barraza & Chen, 2006). These stimuli are sometimes perceived as a luminous transparency bounded by illusory contours that move over the patch that contains the dots. In this case, the patch is perceived as colored with the hue of the dots that define the object (Cicerone, Hoffman, Goudy & Kim, 1995; Cicerone & Hoffman, 1997; Figure 8a). This percept was experimentally confirmed by Chen and Cicerone (2002b) using a color cancellation method. However, unclear is what is perceived when we interpret the stimulus as a surface that moves behind a patch that contains holes through which we see the object. All of the observers in our experiments agreed that in the occluded object configuration (positive disparity) they perceived the contours and shape of the object that moved behind the occluder patch. When asked about whether they perceived the complete boundaries of the object during the stimulus presentation, they answered that they saw the boundaries through the holes in the patch. However, as we explained in the Methods section, the optical array never contained physical contours. We understand that their (and our own) description is related to high-order representation of the occluded object and perhaps the perception of contour segments over the dots that are changing their luminance. We illustrate this percept with the picture shown in Figure 8b. The dotted line represents the object, and the contours that divide the dots into two black and white halves represent the local instantaneous perception of the contours.

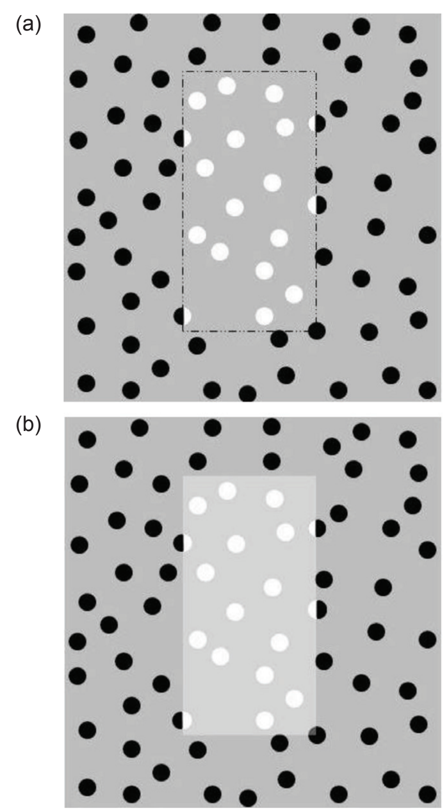


**Figure 8.** Schematics that illustrate the percepts in the two experimental situations: (a) the test region is perceived as a white object (represented with dotted lines) occluded by a holed surface, and (b) the test region is perceived as a luminous transparency that moves in front of a gray patch with dots. The well-defined whitened region illustrates the color spread and illusory contours perceived in this situation. In both cases, the perceived contours that appear on the dots are illustrated here with real luminance contours.

Interestingly, although the experimental data, particularly those from the two first experiments, show no differences when obtained with opposite values of disparity, the percepts associated with these two situations are definitely different, with some characteristics that imply specific processes, such as color spreading in the case of negative disparity (Figure 8a) or the perception of instantaneous contour segments in the case of positive disparity (Figure 8b). This suggests that at some point the information flow would split. According to a parsimony principle, this occurs after the contour integration mechanism. In the following section, we present a conceptual model that explains the role of contour integration in the perception of occluded and occluding objects in the SBF.

### *5.2. Conceptual model*

Figure 9 shows a scheme of the model including intermediate representations of the processed images, in which the case of an occluded object situation is illustrated. The model suggests that the contour integration in the SBF occurs very early in visual processing (perhaps in V1 or V2), due to the concurrent action of spatial and temporal facilitation mechanisms and signals from motion estimation. Although a large amount of evidence shows the critical role of spatial facilitation in the integration of contours (Cass & Spehar, 2005; Field et al., 1993; Polat, 1999; Polat et al., 1998; Polat & Sagi, 1993; Solomon & Morgan, 2000), the role of the mechanisms of temporal facilitation is hardly argued (Cass & Alais, 2006; Barraza & Chambeaud, 2013; Chambeaud & Barraza 2013; Huang & Hess 2008). In the case of the SBF, such a mechanism may allow the system to accumulate information about the contour in time because instant information could be very poor. The image at the output of the Local Edge Estimation Block shows all of the edges present in the image. The four dots over which the contour of the rectangular figure is falling in this instant are printed in black. On the right, we show a zoomed picture of these dots, showing that, in these points, all of the orientations are equally represented. In these positions, the responses of the oriented cells would be elicited by a change of the dot luminance and not by the presence of real contours. Hence, depending on the dot density, the contour of the rectangular figure could be extremely poorly represented at each instant. The temporal facilitation mechanism would allow the system to combine the responses with these luminance transitions that occur at different moments and in different positions along the contour to complete the boundaries of the occluded object in conjunction with the spatial facilitation mechanism. Such temporal facilitation signals were found in cells of V1 (Cass & Alais, 2006; Cass & Spehar, 2005) and could be implicated in the SBF. At this point, motion estimations could be used to bias these facilitations in the direction of motion. We propose that the system uses coarse motion signals that can be extracted, for example, from the displacement of dot luminance modulation.

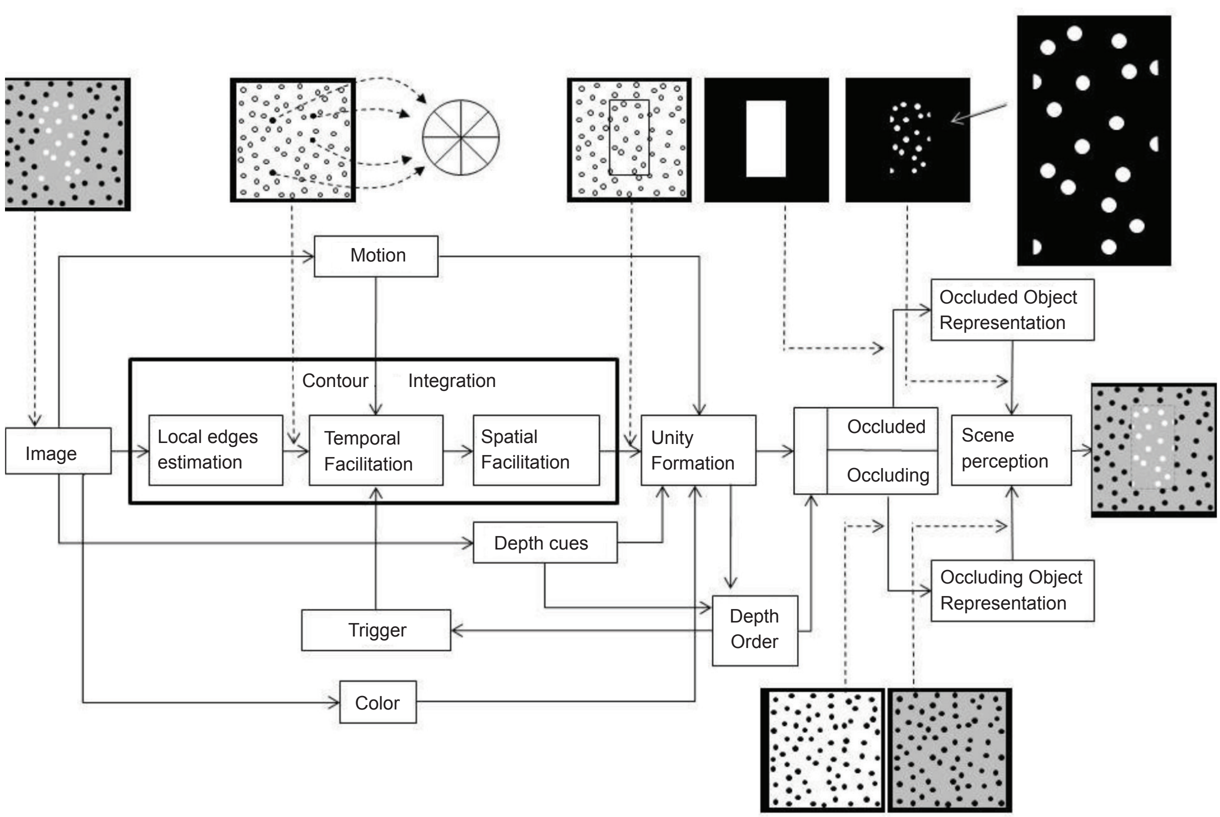


**Figure 9.** Schematic of the conceptual model. In this model, sensory and processing mechanisms are represented with blocks that are connected with solid arrows that indicate the information flow from image acquisition to scene perception. The additional images illustrate the state of processing at each level of the model. The dotted arrows indicate the point at which each image is obtained.

Once the contours are completed, they are used in the following stages to define unities and accomplish object perception. The block we name Unity Formation receives information about the object contours and combines it with the rest of the sensory data, including motion, depth cues, and color, to define the unities that compose the scene (Kellman et al., 2001). For example, in the case shown in Figure 9, the unities are the rectangular object, holed surface, and background. Once unities are defined, the model assigns a depth order to each of these unities. Depending on this order, the unities are represented later as an occluded object or occluder. In the next stages, the model needs to represent the visible parts of the different surfaces. One possibility to instantiate this process is to operate with the reflectance and transmittance of the surfaces. In this case, the surface of the occluder would have a reflectance larger than zero and transmittance equal to zero, while the holes would be assigned a reflectance equal to zero and transmittance equal to 1. This would allow the model to represent the visible parts of the occluded object. In Figure 9, a zoomed image of the visible parts of the occluded object is shown. Notice that this image has contours that are not present in the input image that correspond to contour segments that fall on the occluder dots interpreted as holes.

Finally, the model includes a mechanism that triggers the integration process when a change in the depth order occurs. This trigger avoids the system to integrate contours that belong to objects that are interpreted differently (occluded or occluding).

### *5.3. Occluding object situation*

In this section we discuss the case of white dots that have negative disparity, which produces the perception of a rectangular luminous transparency that moves over a gray patch that contains black dots. Figure 10 shows that the gray patch in this case is interpreted as containing black dots instead of holes and is represented as an occluded object because of its depth order. The moving figure is now represented as the occluder. However, in this case, the combination of depth cues and the color map is inconsistent with the representation of an opaque occluder because the dots do not disappear when the occluder moves over them but instead change their luminance. The combination of cues is also inconsistent with the representation of a transparent object in the classic sense (Metelli, 1974). The system appears to add lightness to the patch (color spreading), whereas the occluder is passing as if it was a spot of light that moves over the gray surface. Chen and Ciccerone (2002a) discussed this issue in detail and argued that one of the main differences between this phenomenon and transparency is that when transparency is perceived, physically differentiated surfaces are conjoined to create a unified perceptual layer (in the SBF, the luminance of the gray patch never changes), whereas in SBF displays, an entirely new surface is created by illusory color spread.

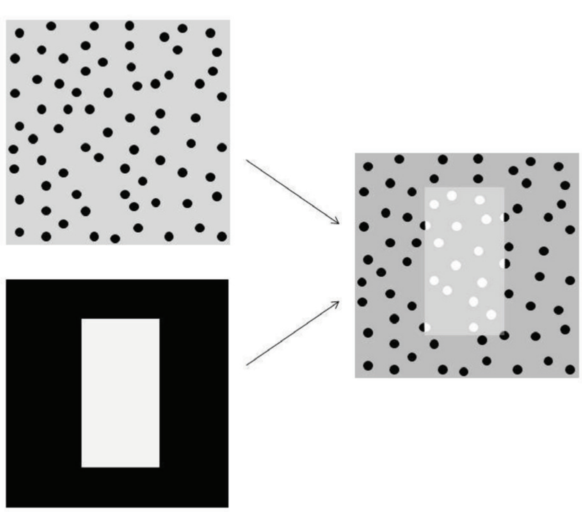

**Figure 10.** The two figures on the left represent the visible parts of the unities that are interpreted as an occluded object (above) and occluding object (below), and the image on the right represents the final perceived image.

### *5.4. Situations in which depth order is ambiguous*

In the last two sections we discussed cases in which there is no ambiguity in the depth order because of binocular disparity. How does the model explain ambiguous percepts that occur in the absence of unequivocal depth cues? The change in the dots' luminance *per se* does not provide a cue to establish depth order, as in the case when accretion and deletion of textural elements produce an effect of an opaque surface that moves over the texture. Our stimuli support two different interpretations that entail different mechanisms, such as the case of "mental representation" of the occluded object and color spread in the case of luminous transparency. This problem is implied in the depth order and occluded/occluding blocks. In the occluded/occluding block, the model has to decide which way the information will follow according to the information that comes from depth order. One may think of the occluded/occluding block as a decision-making block in which the two possible solutions compete with each other to give an explanation of the stimulus. If the depth order information is ambiguous, then the information will flow alternatively through the two possible paths.

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