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Vernier acuity of illusory contours defined by motion

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We present here a series of experiments exploring a special class of visual completion that is strictly tied to the perception of apparent motion. The stimuli consist of sparse random-dot arrays, in which dots remain in place. Changes of luminance or color of the dots at leading and trailing edges of an apparently moving region are integrated over space and time to produce the perception of well-defined contours, shapes, and color. We test how Vernier acuity of apparent motion-defined illusory bars depends on speed, density, and stimulus configurations. We found that higher speed of apparent motion reduces the Vernier acuity thresholds. These thresholds also decrease with increasing density of dots, whose luminance changes provide the apparent motion signal required for the perception of illusory contours. In subsequent experiments, we showed that luminance-defined flankers could seamlessly integrate with and improve the perception of apparent motion-defined contours, reducing their Vernier thresholds.

Keywords: illusory contours, visual completion, motion, Vernier acuity

Introduction

One of the fundamental processes of the visual system is the segmentation of the visual scene into different components. This process requires the extraction of image contours that are not always well defined along their extent due to, for example, occlusion. The visual system is adept at solving this problem by filling in the missing parts. Such filling-in of missing contour information, which is generally known as visual completion, leads to the perception of illusory contours (Kanizsa, 1976).

Motion is a rich source of information for contour completion (Anderson & Barth, 1999; Nawrot, Shannon, & Rizzo, 1996; Regan, 1986; Shipley & Kellman, 1997; Sinha, 2001) because the pattern of change produced by motion over time can provide information about stable properties of the world (Gibson, 1966). One interesting example of contours defined by motion is that produced by the appearance and disappearance of texture elements when a surface reveals and occludes another due to relative motion (Andersen & Cortese, 1989; Bruno & Bertamini, 1990; Bruno & Gerbino, 1991; Shipley & Kellman, 1993, 1994, 1997). For example, Andersen and Cortese (1989) used in their experiments a display in which a random-dot pattern was occluded by a surface of equal luminance as the background. When the surface moved, it produced a pattern of accretion and deletion that revealed the boundaries and its shape. Cicerone and Hoffman (1992, 1997), Cicerone, Hoffman, Gowdy, and Kim (1995), and Shipley and Kellman (1993, 1994, 1997) used a new type of display in which the perceived surface was defined by changing the color of the dots. In this class of stimuli, when the surface moved, the dots did not move or disappear but only changed their color or luminance. These displays produce, in addition to a vivid contour perception, an effect of color spreading (Chen & Cicerone, 2002a, 2002b). In ecological terms, this effect occurs when an object hiding behind a dense foreground formation pops into view the moment when a relative motion is introduced between the object and the foreground.

Figure 1a shows a gray square patch containing a random-dot pattern of black and white dots, which is surrounded by a background of the same luminance as the black dots. When the region containing white dots moves, sharp contours at the boundary of the region are perceived as the borders of a solid white bar. If we add white flankers at the upper and lower boundaries of the gray patch along the extension of the white dot region, we obtain Figure 1b. Most of the observers see this figure as a longer white bar with its middle portion occluded by a surface containing small, sparse apertures. The white flankers are seen as continuation of the bar defined by perceived illusory contours within the gray patch. If we now change the luminance of the background to that of the gray patch (Figure 1c), the perceived moving bar suggests transparency rather than occlusion. Importantly, no visible contours appear on the gray patch in static conditions. We wondered whether the presence of these flankers that may be interpreted as part of the same object as the white dots produces a better perception of illusory contours defined by motion.

We used a Vernier acuity task to evaluate how sharp the subjects perceived the illusory contours (Regan, 1986) in

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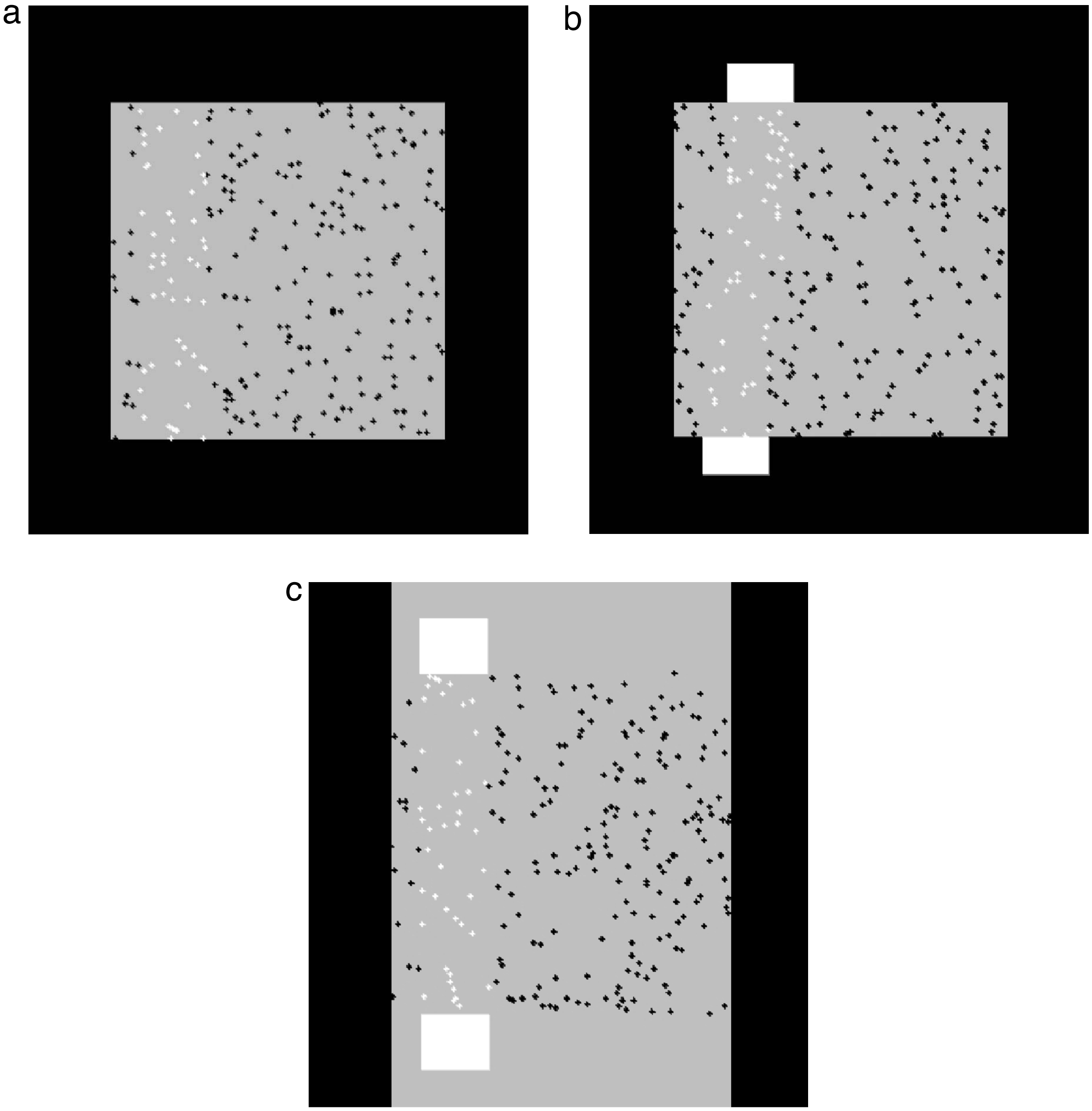

Figure 1. Examples of stimulus configurations. Note that images were pruned to reduce their size. The actual black background was three times wider (16 deg) than the dot area (5 deg). Clicking on the images reproduces the stimulus movies. (a) Configuration A. The black dots have the same luminance as the surrounding area. No dots ever move in this display. Only the luminance modulation that defines an imaginary bar (white dots) moves. Note that in static conditions, the boundaries of the imaginary bar are not visible. Only when the bar moves do the illusory contours appear. This configuration can be interpreted as a white moving bar that is occluded by a gray surface containing small, sparse apertures. (b) Configuration B. This is Configuration A with two real rectangles of the same luminance as the white dots flanking the imaginary bar. Note that the perception of the illusory contours is more vivid in this case. The presence of the flankers strengthens the interpretation of the occluded white bar. (c) Configuration C. The surround luminance of Configuration B is changed to the same luminance as the background within the field of random dots (gray). Here, the depth order is not clear because the black dots cannot be interpreted as part of the far background. The perception of the illusory contours is also sharper than that in Configuration A.

these three configurations. In Regan's experiment, he successfully used this methodology to evaluate the subjects' ability to make spatial discriminations between motion-defined objects. Vernier judgments of two bars defined by the relative motion of dots against their background in a random-dot pattern were surprisingly acute. Importantly, in Regan's stimuli, all dots had the same luminance and the dots actually move relative to each other. Therefore, it is proposed that the test bar is segregated from its background by grouping the dots containing similar motion signals and then combining them to produce a perception of well-defined contours.

Models such as the one proposed by Yuille & Grzywacz (1998) can easily make this work. However, this strategy would not be applied to our stimuli because there is no movement of dots anywhere in the stimuli. The only cue in our displays that could be used for segregation in Yuille and Grzywacz's model is dot luminance but it has been shown that, in the same type of displays, luminance is much less efficient than motion in producing sharp illusory contours (Nawrot et al., 1996).

Methods

Stimuli

Stimulus patterns were created in MATLAB with the Psychophysics Toolbox (Brainard, 1997) and Video Toolbox (Pelli, 1997) and displayed on a calibrated monitor (1,024 × 768 pixel resolution, 16 × 11 deg size, 60 Hz). The stimulus consisted of a rectangular patch containing a random-dot pattern in which no dots ever moved relative to the background. The size of the patch was 5 × 5 deg, and its background luminance was 19 cd/m^2. The luminance of the dots was modulated to define a rectangular test region. Dots located within the test region (white dots) had a luminance of 38 cd/m^2, whereas the rest of the dots (black dots) had a luminance of 0.1 cd/m^2. The width of the test region was 1 deg, and the size of the dots was 11 arcmin. The test region was translated at various speeds (0, 1, 2, 3, and 4 deg/s), with speed being one of the independent variables of the experiment. We chose this range of speeds because we expect that, in this range, the thresholds decrease monotonically (Anderen & Cortese, 1989). This was done by changing the luminance of the dots as the border of the test region reached each dot. The exact time of the luminance change corresponded to the moment in which the border of the test region coincided with the center of the dot. Importantly, the luminance of the whole area of the dots changed in one frame; hence, no edges could appear inside the dots. To display the movies correctly, we synchronized movie frames with monitor frames using the Video Toolbox (Pelli, 1997). Note that the diameter of the dots limits the physical resolution of contours. Therefore, an elongation along the horizontal axis will reduce this resolution. On the other hand, an elongation along the vertical axis will produce physical borders that we want to avoid in this experiment.

We used three different stimulus configurations (see Figures 1a, 1b, and 1c). In Configuration A, the background outside of the patch was set to the same luminance as the black dots. To create Configuration B, we added above and below the rectangular test region, immediately outside the patch area, two solid rectangles of equal width as the test region and assigned them the same luminance as the white dots. The height of the rectangles was 0.5 deg. Finally, in Configuration C, we removed the black background cue by setting the luminance of the surrounding area to 19 cd/m^2.

Procedure

A Vernier acuity configuration is devised by introducing an offset between the upper and lower parts of the test region. Figure 1b shows an example of the stimulus containing such offset. The subjects were instructed to fixate on a marker located in the center of the stimulus and had to answer whether the upper test region was displaced to the left or to the right of the lower test region. The marker disappeared when the stimuli were displayed. Observers reported that fixation was difficult and that they sometimes made involuntary saccades to the test region during stimulus presentation. However, they returned the gaze to the center of the display as instructed.

We used a two-alternative forced-choice paradigm (2AFC) with the method of constant stimuli to obtain the

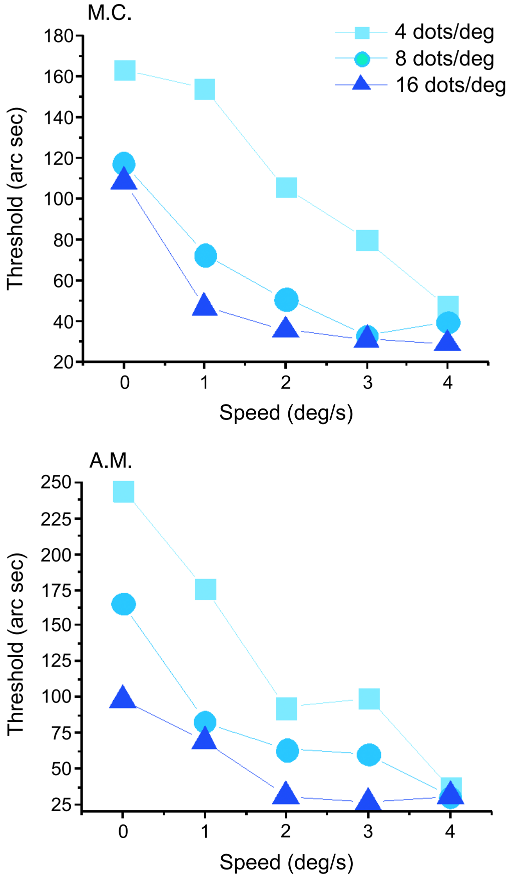

Figure 2. Vernier thresholds in arc seconds as a function of speed for three different dot densities, 4, 8, and 16 dots/deg^2, with stimulus Configuration A. For both subjects, thresholds decrease with increasing speed and density. Note that thresholds obtained with the three densities tend to the same value at high speed.

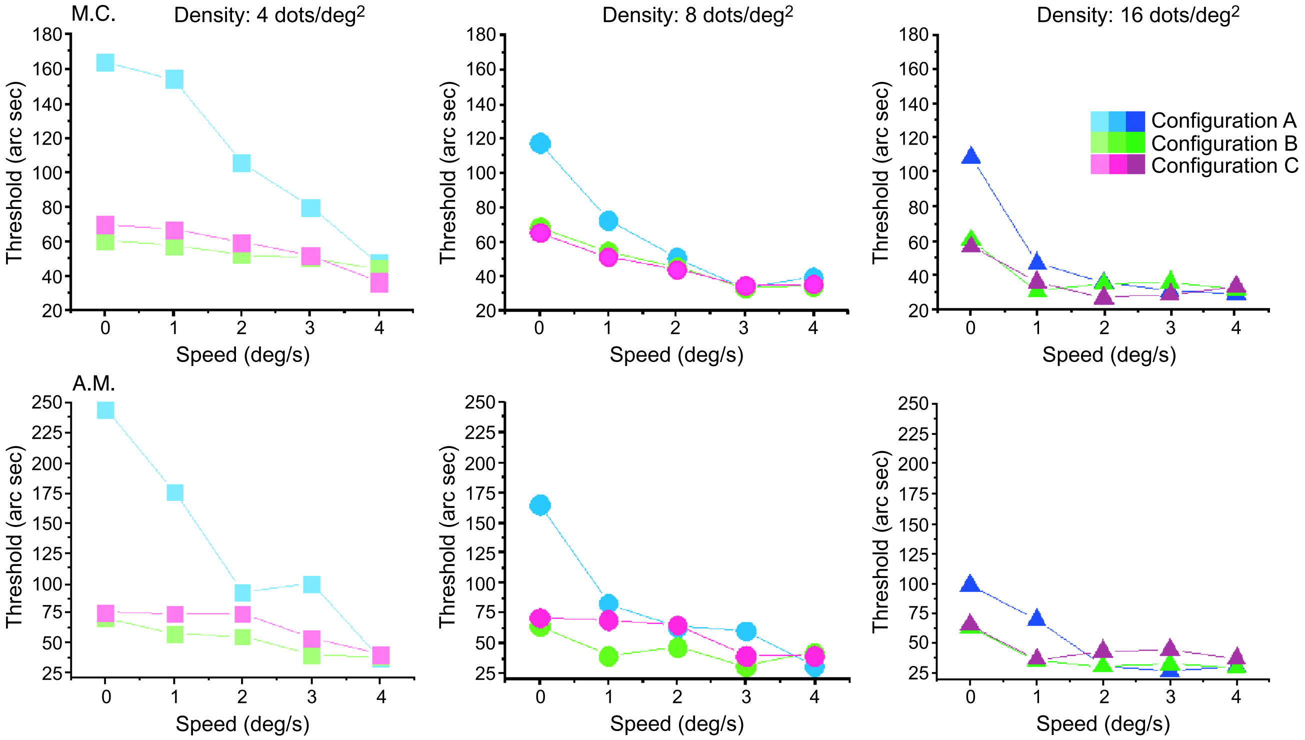

Figure 3. Vernier thresholds in arc seconds as a function of speed for the three stimulus configurations. Each column corresponds to a different density. In this figure, different configurations are represented by different colors, whereas density is represented by color saturation and symbols. The more saturated is the color, the higher is the density. Blue, green, and magenta correspond to Configurations A, B, and C, respectively. These plots show that, for the three densities, thresholds obtained with Configurations B and C are systematically lower than those obtained with Configuration A. Moreover, there are no differences between thresholds obtained with Configurations B and C.

subjects' psychometric functions. To obtain these functions, we used a set of six stimuli in each of the two blocks of trials. Each stimulus appeared a total of 20 times per block. The Vernier threshold was calculated by fitting Weibull functions to the proportion of correct answers.

Subjects

Two naive subjects participated in the experiment. Both had experience in psychophysical experiments and had normal or corrected-to-normal vision. The experiment was performed binocularly with normal pupil. Viewing distance was 1.00 m and was controlled by asking the subjects to place their heads on a chin rest.

Results and discussion

We measured Vernier thresholds as a function of speed for three different dot densities (4, 8, and 16 dots/deg^2). Figure 2 shows the results of Configuration A for both subjects. The plot shows that thresholds decrease with increasing speed and density, which is consistent with previous studies (Andersen & Cortese, 1989; Bruno & Bertamini, 1990) reporting similar results for shape discrimination. To support our data, we tested statistically the dependence of thresholds on speed and density. We added trend lines to the curves relating threshold with speed and found that, in all cases, the slopes of the lines are different from zero and negative with a significance level of .05. The same analysis was performed for threshold versus density, and we obtained the same results.

It is important to note that when there is no motion (speed = 0), subjects are able to perform the task although there is no contour perception. In this situation, the task would be done by comparing the position of individual dots located near the borders of the bars.

Effect of flankers on Vernier thresholds

The next experiment tests whether the presence of flankers improves the perception of illusory contours defined by motion. Figure 3 compares, for each density and subject, the thresholds obtained with the three configurations. Each column contains the data obtained with one value of density. Upper and lower plots correspond to subjects M.C. and A.M., respectively.

Results show that thresholds obtained with the first configuration are higher than those obtained with Configurations B and C. We found no differences between Configurations B and C. Data are supported by a statistical analysis based on a method proposed by Zar (1984), which analyzes two curves by comparing the slopes and intercepts of linear regressions. The method tests the validity of the null hypothesis that the trend lines fitted to the curves corresponding to different configurations are identical. The results of the analysis show that the curves for Configuration A are significantly different (.05 significance level) from curves obtained with Configurations B and C for densities of 4 dots/deg (p = .00006) and 8 dots/deg (p = .048) but not significantly different for a density of 16 dots/deg (p = .071) in the case of subject M.C. Similar results were obtained for subject A.M. (p = .001, p = .015, and p = .063 for densities of 4, 8, and 16 dots/deg, respectively). For both subjects and the three densities, the analysis indicates that there are no differences between Configurations B and C.

Control for zero density

One complication in the interpretation of these results is that, perhaps, the presence of the real bars could be the only cue that will be used by the subjects to perform the Vernier task. To control for this possibility, we created a new configuration (Configuration B1), which is Configuration B but with dot density equal to zero, and measured the Vernier thresholds.

Figure 4 shows the Vernier threshold as a function of speed for three configurations: A, B, and B1. Results show that the threshold for Configuration B1 increases with increasing speed, which is consistent with results obtained from experiments measuring Vernier thresholds for non-abutting lines (Bedell, Chung, & Patel, 2000). Interestingly, when there is no motion (speed = 0), the threshold obtained with Configuration B coincides with that obtained with Configuration B1. This would suggest that, in this condition, subjects use the information of the real bars to do the task. On the other hand, for higher speeds, it appears that the flankers contribute little to the task; thus, the threshold is identical to that when using the illusory contour alone (Configuration A).

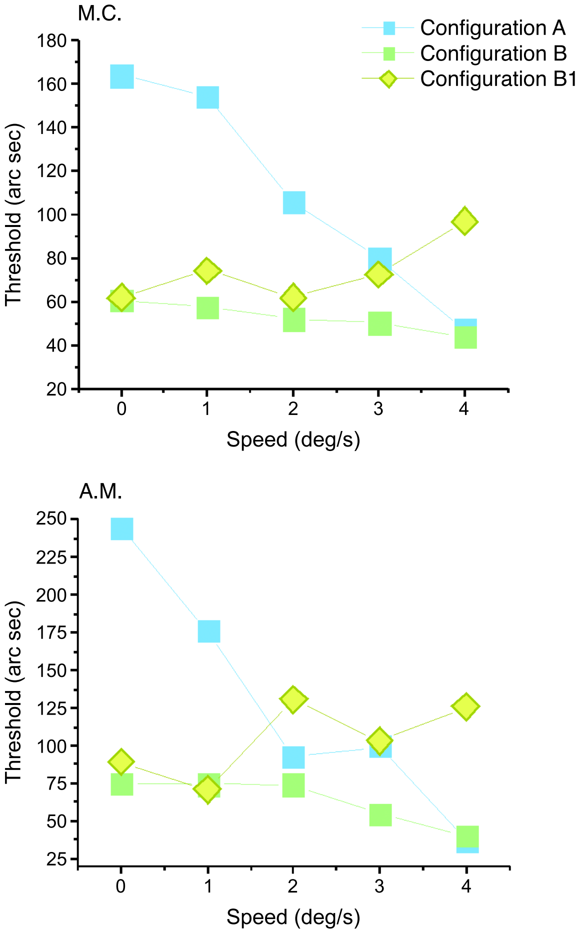

Figure 4. Vernier thresholds in arc seconds as a function of speed for three stimulus configurations: A, B, and B1. The plots show, for both observers, that the threshold for Configuration B1 (dot density equal to zero) increases with increasing speed.

Control for combination of independent information

However, we still cannot conclude that the enhancement of performance for Configuration B is due to a better perception of illusory contours produced by the presence of the flankers. An alternative explanation is that, for intermediate speeds, illusory contours and flankers contribute with independent information for the task, rather than with the perception of sharper contours when seen as one. One way to test the validity of such a claim is to remove all the cues provided by the flankers that may be useful for the Vernier task while preserving the perception of the flankers as integral portions of the moving white bar. If the claim were valid, one would expect no improvement in the performance of such flankers because there is no contribution of Vernier cues of the flankers to the task. In contrast, if what produces the improvement of performance is that the flankers and the test region are perceived as parts of the same object, the performance should improve similarly as in Configuration B. For this control, we devised a new configuration (Configuration B2). Now, the flankers are triangles, in which none of their visible vertices may be used as a cue for the Vernier task. Although the visible parts

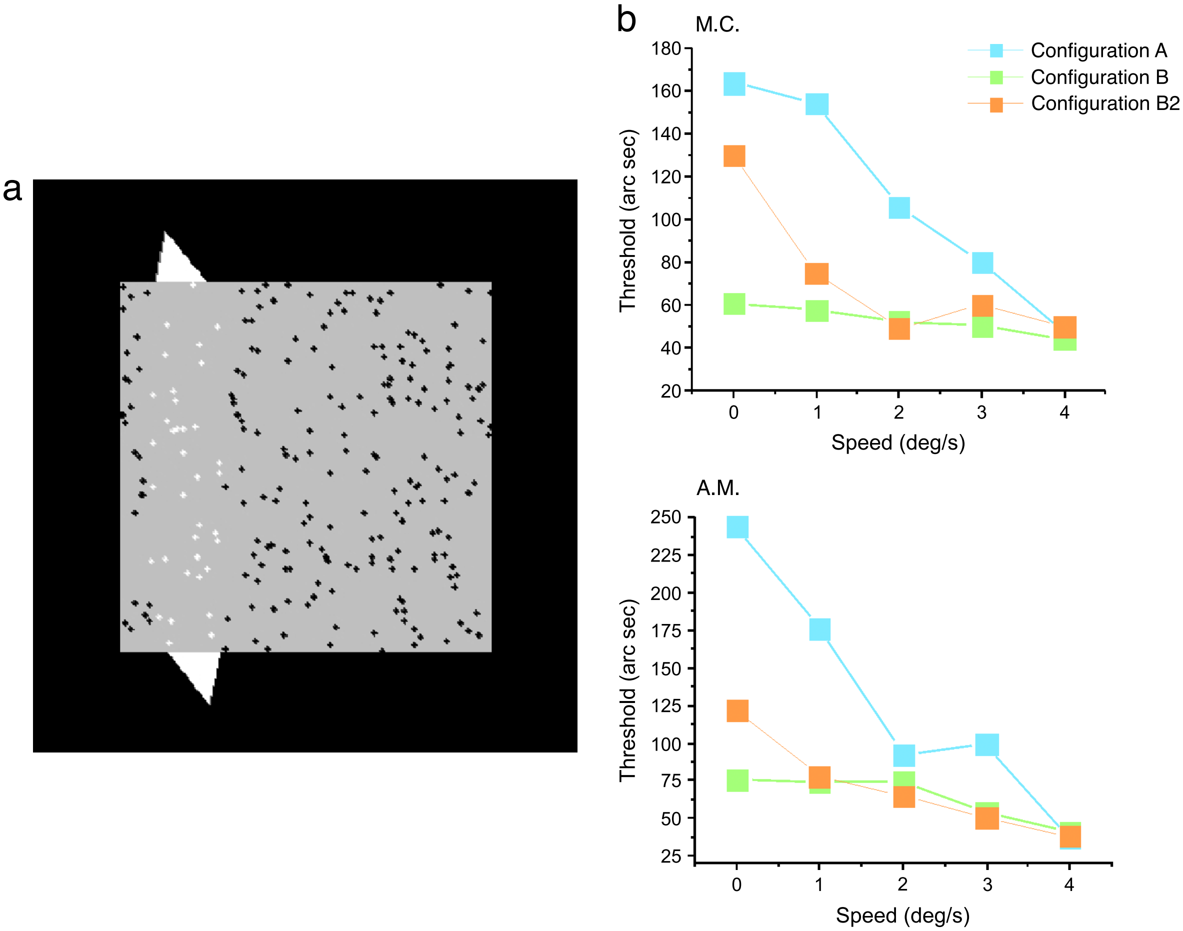

Figure 5. (a) Stimulus Configuration B2. The rectangular flankers of Configuration B are replaced by triangles of the same luminance, in which none of their visible vertices contain useful information for the Vernier task. However, the triangles are the ends of wedge-shaped bars and are seen as such. Clicking on the image reproduces the movie. The reader can see that the triangles and the test bar are perceived as parts of the same object. Moreover, the contours in this configuration are sharper than those in Configuration A. (b) Vernier thresholds in arc seconds as a function of speed for three stimulus configurations: A, B, and B2. The plots show that there is an improvement of performance with respect to Configuration A comparable to that obtained with Configuration B.

of the triangles start exactly on the borders of the gray patch, the actual bases are 0.3 deg inside the gray patch adjacent to the test bar (see Figure 5a). Therefore, these hidden portions of the triangles are seen through dots (motion defined). The total height of the triangles is 1 deg. The test bars' height is reduced to 0.3 deg to joint the triangles and simulate bars with wedge-shaped ends. The upper and lower vertices could take any independent position between the borders of the test region so that none of the visible vertices could be used for the Vernier task. It is important to note that if the offsets of these vertices are always incongruent with the illusory bar offset, it can be used for the task. Also, if there is no offset between these vertices, the shape of the triangles may provide information regarding the illusory bar offset.

Figure 5b shows, for both observers, the results obtained for a density of 4 dots/deg^2, with Configurations A, B, and B2. Except for the static condition, data obtained with Configuration B2 are very similar to those obtained with Configuration B, which supports our hypothesis that the presence of flankers that are perceived as parts of the same object as the test region improves the perception of motion-defined contours. Both observers show an increase of thresholds for speed equal to zero, although the effect is more significant for observer M.C. In both cases, the threshold does not reach the one obtained with Configuration A. The statistical analysis shows that, for both subjects, data obtained with Configurations A and B2 are significantly different (p = .049 for subject M.C. and p = .007 for subject A.M.). The same analysis shows that Curves B and B2 are also significantly different for both subjects (p = .048 for subject M.C. and p = .029 for subject A.M.). However, if the static condition is ignored in the analysis, the probabilities

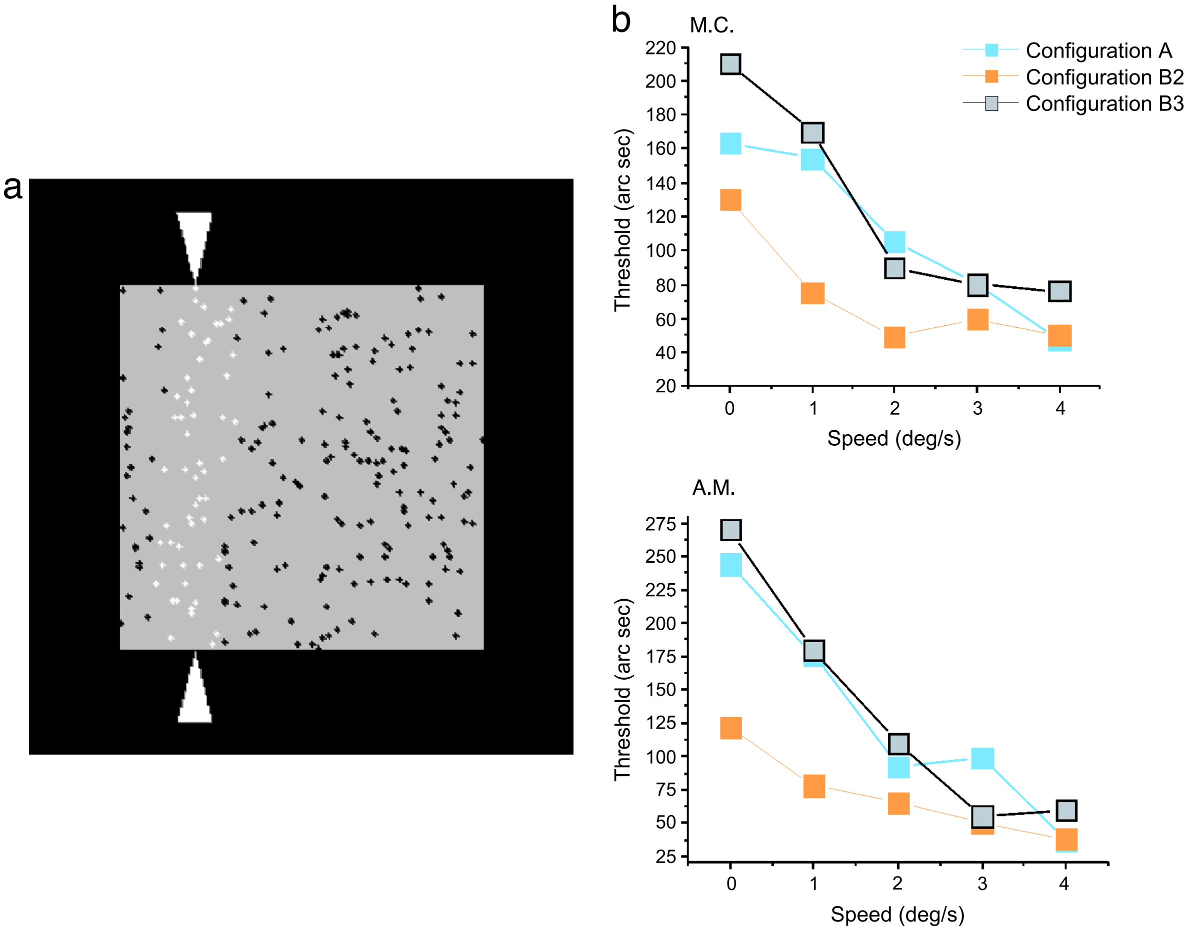

Figure 6. (a) Stimulus Configuration B3. In this configuration, the flanking triangles are not seen as parts of the moving white bar within the gray patch. These triangles are aligned and move coherently with the test bar. (b) Vernier thresholds in arc seconds as a function of speed for three stimulus configurations: A, B2, and B3. In this case, the flankers do not reduce Vernier thresholds of motion-defined contours although they move coherently with the illusory bar.

become p = .31 and p = .07 for subjects M.C. and A.M., respectively, which means that results are statistically identical.

Testing for motion anchoring

Another interesting hypothesis to test is that flankers contribute to the task by anchoring the motion signal, which would help the computation of motion-defined contours. The only source of information available in our stimuli for contour formation is the structured pattern of dot luminance changes. Only dots changing their luminance at the right moment contribute with the motion-defined contour. That right moment depends on the stimulus speed. Therefore, a reliable estimate of speed may help the computation of contours. To test for these possibilities, we devised a new configuration (Configuration B3; see Figure 6a). In this configuration, the triangles are not seen as parts of the illusory bar. Both triangles are always aligned; thus, they cannot be used for Vernier judgments. Their height and width are 1 and 0.5 deg, respectively.

Results of these experiments (Figure 6b) show that performance for Configurations A and B3 are comparable (p = .29 for subject M.C. and p = .34 for subject A.M.), which suggests that moving triangles are not contributing any information for the Vernier task.

Control for eye movements

Both subjects reported that fixation was difficult and that they made involuntary saccades during stimulus presentation. We wondered whether eye movements affect the perception of illusory contours defined by motion in cases where the test bar movement relative to the retina is cancelled out by eye movement. To test for this possibility, we measured Vernier thresholds for Configuration A under smooth tracking condition. To do this, we moved the fixation mark coherently with the test bar (see

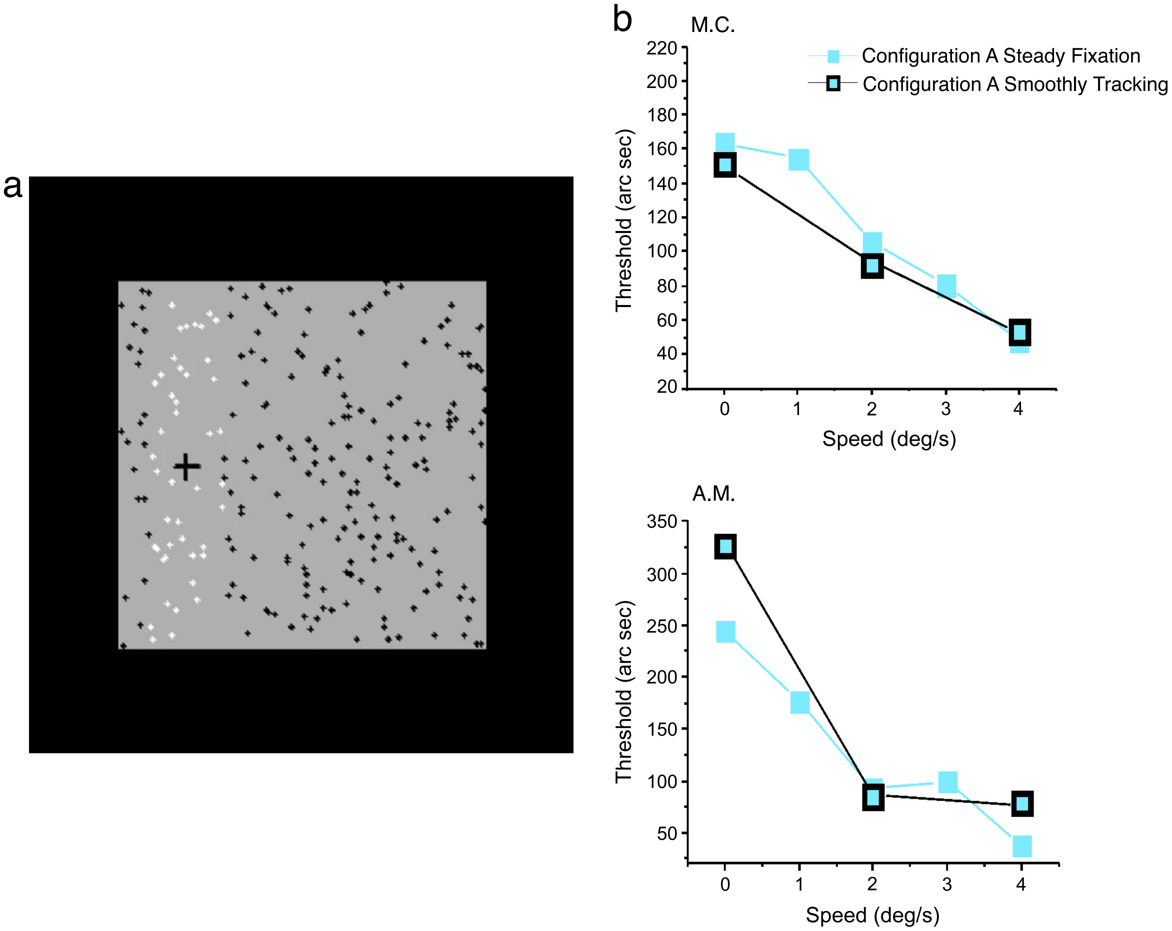

Figure 7. (a) Stimulus Configuration A with fixation mark moving coherently with the test bar. (b) Vernier thresholds in arc seconds as a function of speed for Configuration A with steady fixation and smooth tracking. The plots show that tracking the bar does not affect the Vernier thresholds.

Figure 7a) and asked subjects to track the mark. Figure 7b shows that there are no differences between results obtained with steady fixation and tracking the test bar. This is reasonable because the information used to produce the modal completion is not removed when the subject tracks the bar. The structured pattern of dot luminance changes and the associated motion signal are still present in this situation.

Conclusions

We presented here a series of experiments that explore the phenomenon of contour perception produced by the structured luminance changes of texture elements. Previous investigations extensively studied this class of illusory contours using a shape discrimination task (Andersen & Cortese, 1989; Bruno & Bertamini, 1990; Bruno & Gerbino, 1991; Johnson & Mason, 2002; Nawrot et al., 1996; Shipley & Kellman, 1993, 1994, 1997). Here, we used a technique first introduced by Regan (1986), which consists of measuring the Vernier thresholds between two bars whose contours are defined by motion.

In the first experiment, we found that the perception of illusory contours strongly depends on speed and dot density as previously shown by Andersen and Cortese (1989; Figure 2). The Vernier thresholds decrease with increasing speed, at least in the studied range. This supports the idea that the perception of illusory contours should be mediated by a spatiotemporal integration mechanism (Barraza & Chen, 2004). If the brain estimates the contour based on luminance changes of sparsely located dots occurring along the path of the moving contour, such estimates should improve if more samples of these luminance changes are available within a temporal window. A higher speed or a higher dot density does just that, consequently decreasing the measured Vernier thresholds.

In the second experiment, we tested how the view of a portion of the physical border of the object can affect the perception of the illusory contours. We devised stimuli in which illusory contours are combined with luminance-defined flankers to produce the perception of a single moving bar. We found that subjects' ability to detect a misalignment between the two motion-defined bars is much better when flankers are present (Figure 3). This result is consistent with reports from both subjects and both authors, indicating that the perception of contours is more vivid in these conditions. Data with Configuration B1 (Figure 4) rule out the possibility that the edges of the flankers are the only cues used by the subjects to perform the Vernier task. However, the decrease of thresholds for Configuration B may be alternatively interpreted as coming independently from Vernier cues of the flankers. A new configuration in which flankers and the illusory bar are still perceived as part of the same object is devised, but all their useful cues for the Vernier task were removed. We found with this configuration that the improvement of performance cannot be explained by an independent contribution by the flankers to the Vernier task (Figure 5b). We also tested whether flankers help the task by anchoring the motion signal and found that moving flankers without being seen as integral parts of the motion-defined bar does not improve the Vernier performance in our stimuli (Figure 6b).

Finally, it is shown that tracking the movement of the white bar with the eyes does not seem to affect the perception of illusory contours defined by motion in Configuration A.

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