Neural Networks 24 (2011) 1082–1092

Contents lists available at SciVerse ScienceDirect

Neural Networks

journal homepage: www.elsevier.com/locate/neunet

A new motion illusion based on competition between two kinds of motion processing units: The Accordion Grating

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ARTICLE INFO

Keywords:
Visual illusion
Motion
Projection line
Line of sight
Accordion Grating
Aperture problem
Differential geometry

ABSTRACT

Parametric psychophysical investigations are reported for two related illusory effects that occur when viewing an elementary square-wave grating while making "back and forth" head movements along the projection line. Observers report a non-rigid distortion of the pattern, including: (i) an expansion in a direction perpendicular to the stripes, and (ii) a perceived curvature of the stripes. We investigated these two phenomena independently. The first depends on the classical physiological aperture problem that confronts early cells in the vision system. Interactions between ambiguous and unambiguous motion signals, generated at line interiors and line ends, respectively, can explain why the perceived expansion occurs only in directions perpendicular to the stripes. A simple model is presented and successfully tested by a nulling psychophysical experiment with four subjects. The experiment varies key stimulus attributes that generate ambiguous and unambiguous motion signals. Regarding the illusory curvature, a differential geometry model of the optics of our display, which identifies a non-classical three-dimensional (3D) aperture problem, is proposed (Yazdanbakhsh & Gori, 2011). We tested that model by implementing its closed form prediction of distortion to design displays for a second psychophysical experiment that also uses a nulling technique. Results from four subjects allow the quantification of the degree of perceived curvature as a function of speed, distance and stimulus type (blurred vs. unblurred grating) and are compatible with the predictions of the model.

1. Introduction

A simple pattern consisting of a square-wave grating (Fig. 1a) presents two distinct illusory effects when viewed while making sufficiently large "back and forth" head movements along the projection line. When the head is approaching this pattern, (i) it appears to expand primarily in the horizontal, in other words, in directions perpendicular to the orientation of the stripes, and (ii) the rigidity of the stripes is lost, as the stripes appear to bulge outward.

During pilot testing, observations reported by sixty subjects (73% male, 27% female of ages ranging from 18 to 75 years) indicated the presence of these illusory effects whenever subjects moved their heads, with central fixation, towards the stimulus. The subjects were asked to fixate a central cross that was superimposed on the stimulus and to move their heads quickly from approximately 80 to 40 cm away from the display. A chin rest stopped head movements at 40 cm. Thus, the stimuli ranged approximately from 8.6 × 8.6° to 17.2 × 17.2 deg of visual angle. The procedure could be repeated by the subjects as often as needed to have a clear experience of the illusory effect. The subjects were all naïve, and no information regarding the illusion was provided to them before the test. Subjects were asked to carefully report what they perceived. The grating was commonly described as non-rigidly expanding horizontally and thereby deforming relative to its baseline shape when viewed statically. On the other hand, when moving the head away from the pattern, an opposite shrinking distortion was perceived. Observers frequently referred to a loss of rigidity of the stripes and described the phenomenal distortion as the stretching of rubber or as similar to the deformations of an accordion while being squeezed, characterized by horizontal compression and expansion. We thus call this perceptual phenomenon the "Accordion Grating illusion" (AGI).

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doi:10.1016/j.neunet.2011.06.017

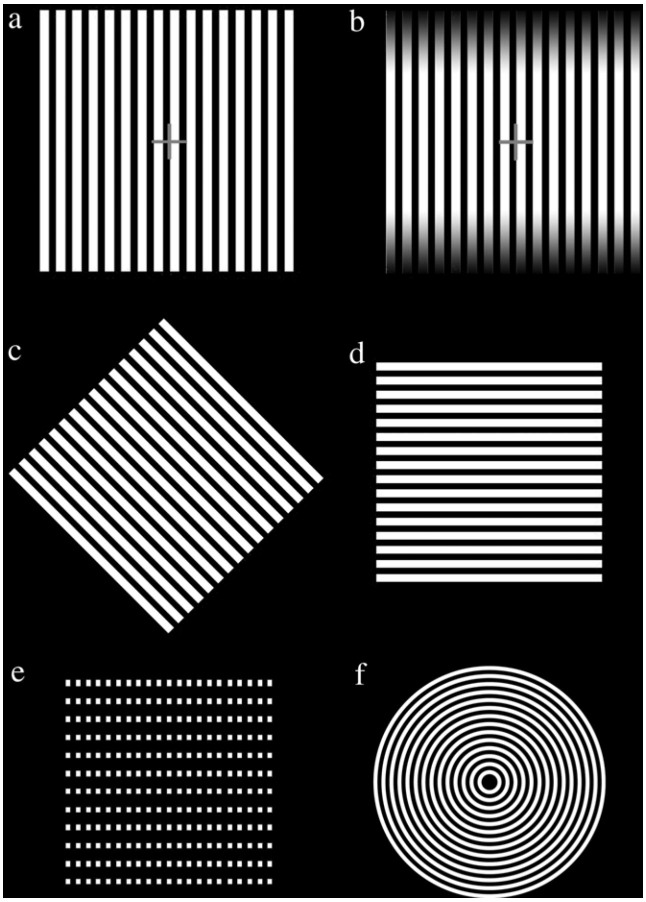

Fig. 1. (a) The Accordion Grating. (b) A version of the AGI that is blurred in the vertical direction. (c)–(f) The stimuli used in Experiment 1. In (a) and (b) a fixation cross is superimposed on the stimuli. To experience the illusion, fixate the cross and move your head back and forth over distances approximately 80–40 cm from the page along the projection line.

The two illusory effects of expansion and deformation from straight to curved lines were next tested separately, both because they are phenomenologically distinct and because, as we will argue, they originate from different mechanisms, namely, circuits of the visual system that are meant to overcome the classical (physiological) aperture problem and the newly identified 3D aperture problem.

The classical aperture problem confronted by cells with spatially limited receptive fields can be viewed as follows: each neuron in the visual system is sensitive to an input in a small portion (the aperture) of the visual field, as if each neuron is looking through a window. The motion direction of a contour is ambiguous, because the motion component parallel to the line cannot be measured based on the visual input. This means that a variety of contours with different orientations moving at different speeds can cause identical responses in a motion-sensitive neuron. The 3D aperture problem is introduced and formulated in detail by Yazdanbakhsh and Gori (2011). We first consider the expansion effect in the AGI.

2. Expansion in directions that are perpendicular to the stripes

Since our experiments were motivated by predictions of a simple model, we present that model next. A reader who wishes to focus on experimental methods could skip Section 2.1 and proceed directly to Section 2.2.1.

2.1. A model accounting for the expansion effect in the AGI

The expansion effect in the AGI may be understood as a consequence of coding of ambiguous and non-ambiguous motion signals afforded by the stimulus (Gurnsey, Sally, Potechin, & Mancini, 2002; Yazdanbakhsh & Gori, 2008) or, equivalently, as a result of competition between motion signals originating from two different classes of motion processing units (Gori & Yazdanbakhsh, 2008; Grossberg & Mingolla, 1993; Lorenceau, Shiffrar, Wells, & Castet, 1993). Supported by electrophysiological findings (Yazdanbakhsh & Livingstone, 2006), we suggest that two different kinds of early motion processing neurons are involved in the expansion effect, contour units and end-stopped units, as in the Gori and Yazdanbakhsh (2008) model's account of the Rotating Tilted Line Illusion (RTLI) (Gori & Hamburger, 2006).

First, consider motion processing units that maximally respond when the full length of a line passes over their receptive field (called *contour units* hereafter). These units face the aperture problem: they can only pick up the normal component of velocity from any straight line or edge that fills their receptive field (Adelson & Movshon, 1982; Fennema & Thompson, 1979). The second type of motion processing unit responds to a moving line best when one or other line ends (terminators) fall within their receptive field. Such units, symmetrical or asymmetrical *end-stopped* neurons, can indicate the true direction of motion of the entire line from information afforded by the line-end motion (Mingolla, Todd, & Norman, 1992; Pack, Livingstone, Duffy, & Born, 2003). An idealization of these two types of motion processing units appears in Fig. 2.

Let us apply the simple schematic model of Fig. 2a and b to the AGI's expansion effect. When approaching the AGI with central fixation, radial expansion motion of the grating on the retina is produced everywhere. (Fig. 2c depicts this motion via solid black arrows for the outermost line ends only). Assume that the motion of every stripe is registered by some number N of contour units and an equal number N of end-stopped units. In other words, every part of visual cortical space has contour units and end-stopped units tuned to a variety of motion directions. It happens that the AGI display will stimulate networks of contour and end-stopped units in particular ways. In Fig. 2, we depicted an idealized motion registration of a single bar where N contour units and $2M (M \ll N)$ end-stop units will respond to the elongated bar. Those end-stopped units whose receptive field include a stripe end will signal the correct direction of motion (Fig. 2a, solid black arrows in Fig. 2c), while the contour units signal an orthogonal to the bar direction rather than the veridical motion direction (radially away from the fixation point) that is available at the ends of the stripes (Fig. 2b, dashed grey arrows in Fig. 2c).

If there were some process ensuring perception of rigidity for each stripe, we could next assume that some weighted average of responses from end-stopped units and contour units would determine the perceived direction of motion for a particular stripe. What actually happens is more interesting, however. First, the appearance of the stripes becomes non-rigid, as is considered at length in Section 3. Second, as we will see in this section, evidence from published studies indicates that there is a temporal evolution of the contributions of signals from end-stopped and contour units to a percept, rather than a fixed ratio of influences.

In a simplified formalism, consider the end-stopped and contour units E_i^k and C_i^k that are tuned to motion direction k at location i along a particular stripe (Fig. 2). The overall activity of each set of E and C units for each direction is determined by

$$E^k = \sum_{i=1}^{N} E_i^k, \quad \text{and} \tag{1}$$

$$C^k = \sum_{i=1}^{N} C_i^k. \tag{2}$$

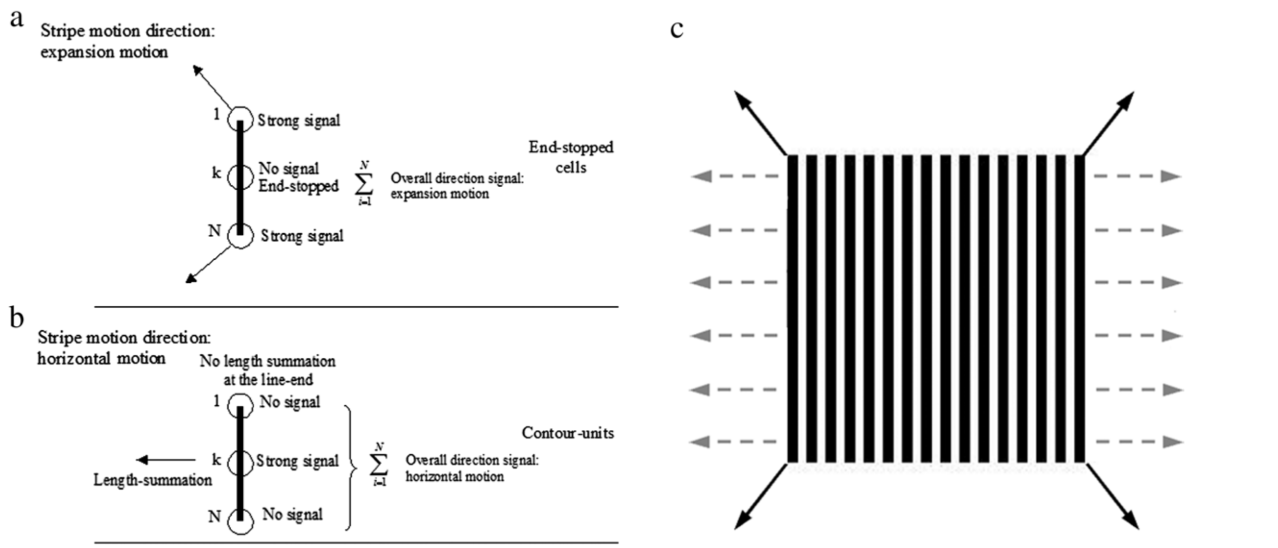

Fig. 2. (a) and (b) Idealized depiction of the two types of motion processing units that are proposed to be involved in the AGI illusory expansion and deformation effects. (c) The direction signalled by the end-stopped units (solid black arrows) and by the contour units (dashed grey arrows) while the observer's head is approaching the AGI display.

The net result of such calculations for an expanding stripe is shown in Fig. 2.

As can be seen in Fig. 2a, at the end of the lines (units 1 and N) it is the end-stopped cells that are the active units, while the end-stopped units within the line do not contribute to the summation in Eq. (1), because end-stopped units do not respond to contours that fill their receptive field. The contour units instead get their optimal input from the interior of the line, away from the line ends. Due to their length summating nature, they get sub-optimal input at the line ends, because their receptive fields are not filled by the line.

The net result for Eq. (1) is to signal radial expanding motion, while the result of Eq. (2) is to signal horizontal translating motion. We next assume that the weighted sum of (1) and (2) ($w_E E^k + w_C C^k$, where, for example, $w_E = w_C = 0.5$) determines the final direction at every location of the display, but we consider this calculation without any additional (and incorrect) assumption that would force a rigid percept for each stripe.

Along the interiors of the stripe segments, such a weighted average would reflect the "votes" of the contour units more than those of the end-stopped units, given that the length of the stripe is long enough to weight the summation in (2) higher than that in (1). Consequently, the subject will see the horizontal expansion of the stripe pattern more strongly away from the stripe ends. Note that Pack and Born (2001) have shown that the resolution of the physiological aperture problem, where signals originating at line ends come to shape responses of units that initially pick up only the normal component of line velocity, takes time (on the order of 100 ms.). To begin to assess the time course of the AGI expansion effect, it is sufficient to move one's head towards Fig. 1a very slowly and to note that the illusory expansion and deformation effects break down, exactly like Yazdanbakhsh and Gori (2008) described for the RTLI pattern. Lorenceau et al. (1993) anticipated such an effect studying direction discrimination for lines moving obliquely relative to their orientation. They found systematic errors in direction discrimination that were described as a result of a competition between ambiguous velocity signals originating from contour and line terminator processing units.

Our model makes predictions that we experimentally tested:

(1) An appropriately blurred version of the AGI should provide a stronger expansion to the stripes than the original pattern, because the blurred version reduces the signal to the end-stopped neurons compared to the signal to the contour units.
(2) A change in orientation of the AGI should result in a change of the direction of the illusory effect but not in a change of the strength of the illusory distortion. The contour units will signal the motion to the stripes irrespective of the orientation of the grating.
(3) A grating composed by very short stripes should reduce the illusion. The very short stripes weight the percept towards the motions signalled by end-stopped units more than those signalled by the contour units.
(4) If the grating is arranged as a concentric circle pattern, the illusion should disappear, because all the motion processing units will signal the same true direction of motion, and therefore the weighted average of their signal would be identical. Specifically, the contribution of end-stopped units will be eliminated.

The aim of Experiment 1 is to test the predictions made by the model.

2.2. Experiment 1

Experiment 1 is based on a nulling paradigm. We sought to minimize the perception of illusory motion by an opposite physical motion; the amount of physical motion sufficient to break down the illusion is a measure of its strength. In the specific case of the AGI, because the expansion effect consists of perception of a "larger than real" motion in a direction perpendicular to the orientation of the stripes, then to null the illusion we reduced the physical motion in that direction until the subjects reported that the perceived motion perpendicular to the stripes was the same as the motion parallel to the stripe. In other words, the nulling point was the setting for which the subject experienced the "best available" radial motion. As shown in Fig. 3, the nulling was achieved through a non-rigid change of the spacing of the stripes and of the thickness of the stripes from frame to frame in the video sequence for a given trial as explained in Section 2.2.1.2.

Based on the model predictions, we expected that:

(1) The extent of the compensatory reduction of the physical motion perpendicular to the stripes that was necessary to null the illusory effect would be close to 0 when the expansion/contraction speed was very slow. In fact, the aperture problem would be solved by larger receptive fields in

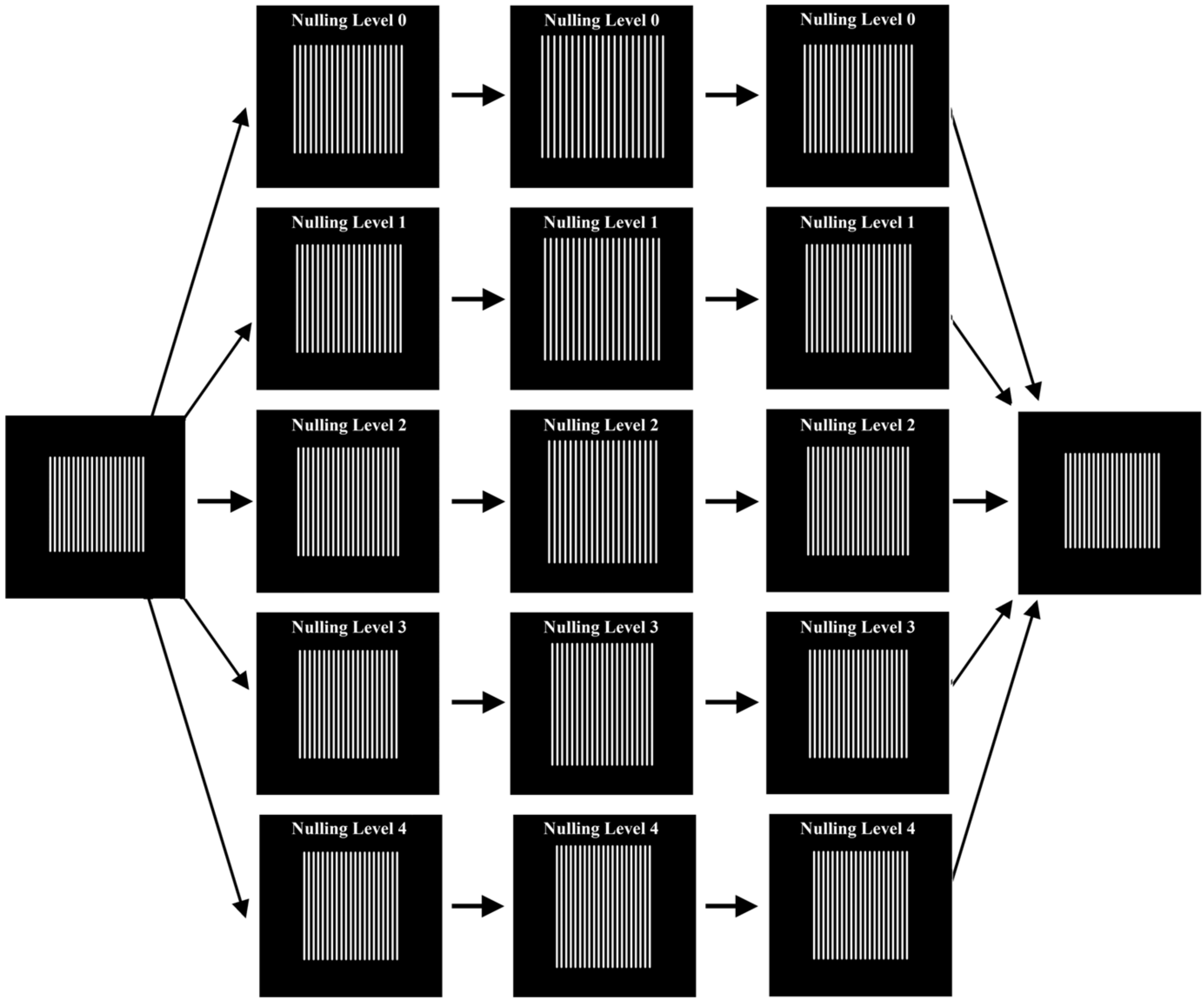

Fig. 3. A loop of expansion/contraction of the grating for the five levels of the nulling stimulus. With level 0 the physical aspect ratio of the square is maintained when the grating expands or contracts. For other levels, the motion perpendicular to the stripes is reduced until it is completely absent at level 4. The subject has to choose at which level of distortion the grating appears as an expanding and contracting square (i.e. when the perceived horizontal/vertical ratio is equal to 1).

higher visual cortical areas or by the propagation of the signals from the end-stopped neurons if the motion is slow enough. Since the present description of our model is intentionally simple and "static", it cannot capture such dynamic effects.

(2) If the visual system is not able to at least partially solve the aperture problem, the maximum compensation, that in our case would appear as a square that enlarges only in the direction parallel to the stripes with the absence of motion perpendicular to the stripes, will be needed to null the illusion. On contrary, if a smaller amount of the distortion was enough, that would indicate that visual system can partially solve the aperture problem for our stimuli.

2.2.1. Methods

Although our pilot experiment and the demonstration for the reader described earlier in this article depend on voluntary head movements by an observer, Experiment 1 used a more controlled procedure whereby stimuli were dynamically manipulated while an observer's head was at rest. A chin rest was used to stabilize the head. Viewing was monocular, enforced by a screen placed in front of one eye.

2.2.1.1. Subjects. Four naïve subjects (mean age 35 yrs; age range = 33–37) participated in the study. All had normal or corrected-to-normal visual acuity.

2.2.1.2. Stimuli. We created a series of animations with white stimuli on a black background, each with a different level of physical distortion of the aspect ratio of the overall square envelope of the canonical AGI stimulus depicted in Fig. 1a. Five levels of distortion were applied (from 0 to 4) as shown in Fig. 3. The ratio of expansion/contraction for a given stimulus in the direction perpendicular to the stripes versus parallel to the stripes was the independent variable.

We label each of the five nulling animations with an integer, i, from 0 to 4. Let the ratio of stimulus expansion/contraction perpendicular to the stripes to the expansion/contraction parallel with the stripes equals $(4 - i)/4$. For $i = 0$, there is no aperture problem to null, so the ratio is 1. For $i = 4$, its maximum value, the ratio is 0, as the grating only elongates parallel to the stripes, connoting the greatest possible aperture problem. Six qualitatively different base stimulus patterns were used in this experiment: (1) the normal grating of Fig. 1a, (2) a grating with a Gaussian blur applied (Fig. 1b), (3 and 4) the same grating as in Fig. 1a

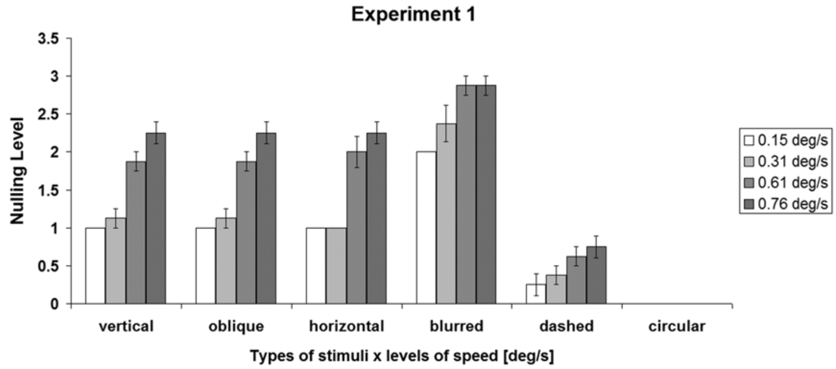

Fig. 4. The graph showing the results of Experiment 1. Error bars represent standard errors and their absence means that no variance was present in the data.

rotated by 45° or 90° (Fig. 1c and d), (5) a grating composed of vertically oriented fragmented stripes (Fig. 1e), and (6) a pattern of concentric circles (Fig. 1f). The distance between stripes was always increasing from 9.4 to 9.8 cm, while the width was a function of the distortion level (from 0 to 4, described above). Four speeds (v) were used: 0.15, 0.31, 0.61, 0.76 deg/s. In total we used 120 movies (6 types of stimuli $\times$ 5 levels of distortion $\times$ 4 animation speeds). A red fixation point was superimposed on the centre of each stimulus.

2.2.1.3. Procedure. A chin rest set the subjects' viewing distance to 45 cm from the 28 $\times$ 21 cm monitor (Sony Trinitron Color E100P). Subjects viewed a series of movies characterized by different levels of distortion and had to choose the level of (physical) distortion of the stimulus (that was expanding and contracting on the screen) that best nulled the illusory expansion, thereby creating an apparent aspect ratio of 1 between the perpendicular- and the parallel-to-the-stripes distances. We presented white stimuli on a black background in a dark room in order to minimize the information about the veridical expansion/contraction of the grating due to the physical distance variation between the grating itself and the screen frame. The subjects were allowed to view any of the five levels of distortion for any given trial, and to go "back and forth" between adjacent levels, until they were sure that a given level of distortion was the best available choice for making the aspect ratio between the perceived horizontal and vertical grating dimensions equal to 1. All the subjects did this task for all the stimulus types and for all the movie speeds.

2.2.2. Results

The results are summarized in Fig. 4. A repeated measures ANOVA yielded main effects of stimulus type ($F_{(5,15)} = 260.21$; $p < .001$) and movie speed (one tailed $F_{(3,9)} = 62.97$; $p < .001$).

In the blurred vertical grating the extent of distortion needed to nullify the illusory effect was significantly larger than the amount sufficient to null the illusion in the sharp grating (single tailed $F_{(1,3)} = 961.00$; $p < .001$). Comparing the three grating orientations, the amount of the distortion necessary to have no illusory effect was not statistically different for 0°, 45° and 90° of rotation ($F < 1$).

Comparing the vertically oriented grating with its dashed version, significantly smaller levels of distortion were necessary to compensate the dashed grating (one tailed $F_{(1,3)} = 96.33$; $p = .001$).

Finally, no illusory effect was found with the circular pattern.

2.2.3. Discussion

The results of this experiment are consistent with the predictions of the model and allowed us to compare the strength of the illusory effect at different speeds. The stronger effect obtained by the blurred grating supports the hypothesis that end-stopped neurons help to signal veridical motion in displays such as ours. By blurring the line ends and reducing the activity of the end-stopped neurons, the contour units that signal the motion direction perpendicular to the stripes face less competition from the end-stopped units, and so the illusory effect appears more vivid.

Rotating the stimulus orientation changed the direction of the distortion to be perpendicular to the stripes, while the strength of the illusion remained the same. This is in agreement with the hypothesis that the overall perceived motion direction is the one signalled by the contour units, which is always perpendicular to the stripes. The reduced illusory distortion for the dashed gratings is consistent with the hypothesis that, when the stripe segments are small enough to fall into the receptive fields of the motion processing units, in particular the end-stopped ones, the aperture problem is reduced and the illusion breaks down. The complete absence of an illusory effect for the concentric circle pattern also supports the hypothesis that, when all the motion processing units involved signal a globally consistent and locally veridical directions of motion, the AGI does not occur. These results together support our hypothesis that the aperture problem is at the root of the AGI's characteristic percept of expansion perpendicular to the stripes in the presence of radial motion on the retina.

The model described in Section 2.1 and in Gori and Yazdanbakhsh (2008) can be thought of as a key functional component "extracted" from more complex motion processing models (Bayerl & Neumann, 2004; Berzhanskaya, Grossberg, & Mingolla, 2007; Chey, Grossberg, & Mingolla, 1997; Grossberg & Mingolla, 1993; Grossberg, Mingolla, & Viswanathan, 2001). In these models the output of end-stopped units is often dispositive for the final model percept. That is, when processing a moving line segment, the signals from numerically fewer end-stopped units usually overcome the numerical superiority of aperture-ambiguous signals from contour units, thereby allowing for, say, veridical perception of rightward motion for a line that happens to be diagonally oriented in the visual field. The mechanisms for accomplishing this "undemocratic" feat include the down-regulation of aperture-ambiguous signals along the interiors of lines by shunting cross-direction competition among contour units. As anticipated from psychophysics by Lorenceau et al. (1993) and Mingolla et al. (1992), first computationally simulated by Chey et al. (1997), and confirmed by single-unit electrophysiology by Pack and Born (2001), however, this process for global resolution of the aperture problem takes time. The appeal of the AGI lies in large part in our ability to set the balance between the effects of end-stopped units and contour units by the simple voluntary regulation of the temporal frequency of expansion/contraction speed. The results for variations in speed are consistent with the time required for integration processes (propagation of the end-stopped neuron signals and/or larger receptive fields in high cortical area contribution) during observation

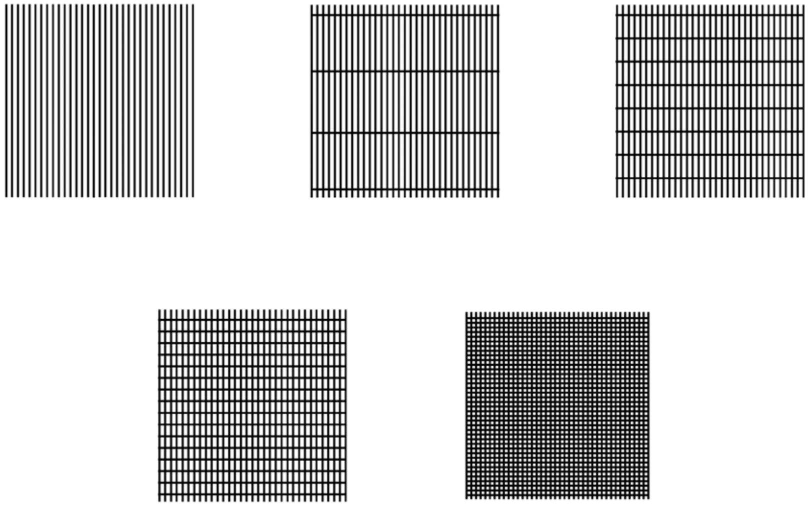

Fig. 5. The stimuli used for the second pilot experiment regarding the illusory curvature.

of the AGI, as reported for MT neurons by Pack and Born (2001) in macaque monkeys and inferred psychophysically for humans by Lorenceau et al. (1993).

Finally, the distortion necessary to null the illusion is less than what would be expected if the visual system was not able to partially correct the aperture problem. This result suggests that, even when the illusion is present, the visual system is doing some correction. Such is observed in other motion illusions as, for example, in the Unchained Dots Illusion (Gori, Giora, & Stubbs, 2010), where the veridical motion partially corrects the illusory motion resulting in a perceived motion direction that is a perceptual compromise between the two directions.

3. Curvature of the stripes

We next investigated the reported loss of perceived rigidity of the stripes, resulting in an outward curvature of the stripes when one approaches the AGI pattern. A similar phenomenon was described by Foster and Altschuler (2001) in a more complex pattern: a checkerboard grid. They reported that, when approaching the grid, a spherical bulge protruding from the centre of the figure was perceived. The AGI is interesting because long lines have no singularities except the line ends, while a checkerboard has many line intersections that could reduce the aperture problem and the illusory effect. To test how the number of intersections affects illusory curvature we ran another pilot experiment. Five naïve subjects (mean age 34 yrs; age range = 31–35) participated in the study. All had normal or corrected-to-normal visual acuity. Five stimuli (the intersection numbers were 0, 123, 264, 528 or 1560) were used in this experiment (depicted in Fig. 5). A superimposed middle grey cross helped the subjects to fixate. The five stimuli were presented randomly on a 28 × 21 cm monitor Sony Trinitron Color E100P. The subjects had to fixate the central cross superimposed on the stimuli and to move the head back and forth between 80–40 cm from the screen, while a chin rest stopped the head movement. Thus, the stimuli passed form 8.6 × 8.6° to 17.2 × 17.2 deg of visual angle.

The procedure could be repeated by the subjects until they experienced a clear percept of the illusory effect. The task was to rate the strength of the illusion on a six point scale in which 0 means no illusory distortion and 5 means strong illusory distortion. All the stimuli were presented four times in random order. A familiarization phase before the experiment instructed the subjects to rate the blurred grating as 5 and a black square of the same dimension of the grating (where no illusory distortion was present) as 0. These two patterns were not in the experimental session but served as anchors for the rating scale to be used for the pilot experiment. All the results are summarized in Fig. 6. A statistical difference, in terms of illusory strength, is present inside this set of stimuli as showed by the repeated measures ANOVA ($F_{(4,76)} = 133.07$; $p < .001$). Increasing the intersection number decreases the illusion significantly, showing that the grating is the strongest pattern to elicit the illusory curvature. The presence of the illusory effect in the grid simply shows that the intersections are not close to each other to completely eliminate the effects of the aperture problem.

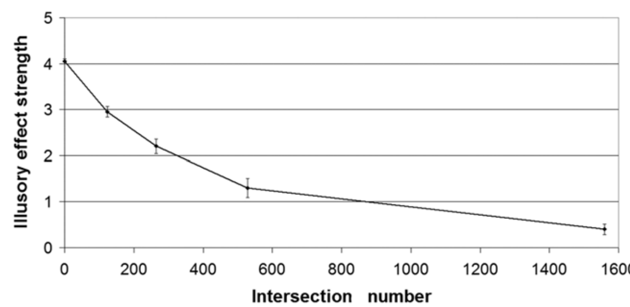

Fig. 6. The graph showing the results of the preliminary experiment regarding curvature. Error bars represent standard errors.

Experiment 2, described in Section 3.1, was designed to empirically test a mathematical model proposed by Yazdanbakhsh and Gori (2011), which accounts for the loss of stripes rigidity in the AGI. This model analyses the AGI for the monocular condition based on the geometry of light projection and the aperture problem.

The classical two-dimensional (2D) aperture problem cannot address this observed curvature distortion. Yazdanbakhsh and Gori (2011) instead proposed an analysis based on differential geometry for a three-dimensional (3D) aperture problem, which predicts the vivid perception of curved "bulging" sides of the AGI pattern. The 3D aperture problem can be defined as the ambiguity of true direction of motion faced by motion detector with limited receptive field size, originating not only from a limited 2D aperture view, but also from the 3D geometry.

The following equation stemming from the Yazdanbakhsh and Gori (2011) model yields the perceived motion as a function of the position of each point of an AGI stimulus for a fixed viewing distance:

$$v_{\perp} = nvf^{ap}(n, x), \quad (3)$$

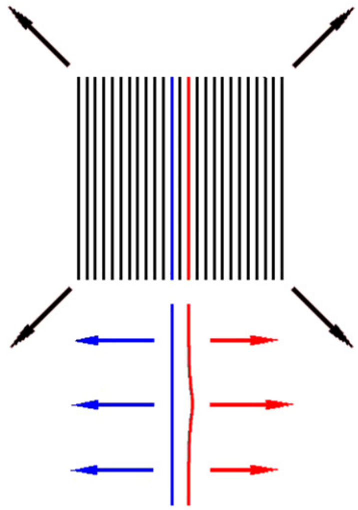

Fig. 7. Two selected stripes from the AGI pattern presented different perceptive results if their physical radial motion (black arrows) is computed considering the 2D aperture problem (blue) and the 3D aperture problem (red). Only if the prediction based on an analysis of the 3D aperture problem is considered will the illusory curvature be obtained. Note that it is only the proportion of the lengths of the vectors, not their absolute length, that is communicative. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

where n is the stripe index, v is the relative speed of two consecutive stripes, x is the elevation of a point on the stripe and $v_{\perp}$ is the 3D aperture component which we attribute to the perceived motion and finally $f^{ap}(n, x)$ is the distortion function:

$$f^{ap}(n, x) = \frac{na\sqrt{n^2a^2 + d^2}}{\sqrt{n^2a^2 + x^2}\sqrt{x^2 + n^2a^2 + d^2}}, \quad (4)$$

where a is the distance between the consecutive stripes and d is the viewing distance from the stimulus.

The obtained simulations for different distances from the screen showed by the model (see Figure 9 in Yazdanbakhsh and Gori (2011)) are clearly close to what is seen observing the AGI expanding on the screen and it is characterized by strong curvature in the middle of the grating but less curvature in the periphery. Fig. 7 depicts the expected perceptual result for two selected stripes, after radial motion (black arrows) occurs over a brief interval, one calculated with the traditional 2D aperture problem (blue) and the other calculated with the 3D aperture problem (red).

The resulting non-rigid curvature illusion has the hidden assumption of the presence of the 2D aperture problem even close to the line ends, which naturally do not suffer from the aperture problem because they are processed by the end-stopped neurons signalling the veridical motion. In this sense, all of the predicted displacements can be attributed to one of the two situations: (1) When the line ends are somehow blurred and therefore their end-line signals are minimized. (2) Only the mid-portion of the stimulus well far from the line ends is considered.

In conclusion, the AGI pattern curvature based on the model simulations was not arbitrary; on the contrary, it can be described mathematically based on an analysis of the 3D aperture problem for a given distance and pattern size. Based on that model we constructed the next nulling experiment to empirically test the simulations of the model for different distances from the screen and speed of expansion of the AGI, and also to test whether part of the 3D aperture problem is solved by the visual system at certain speeds and distances.

3.1. Experiment 2

This experiment is based on a nulling paradigm; the inversion of the closed form for distortion, in the above, allows us to observe whether we can eliminate the apparent non-rigidity. On the basis of the model discussed in Section 3, we expected that:

(1) The compensation necessary to have no illusory effect would be higher in the blurred patterns, because the blurred AGI should reduce the end-stopped neurons' activity.
(2) The compensation necessary to have no illusory effect would be slightly higher when the observer was closer to the screen, because decreasing d in the distortion equation makes the ratio of the terms containing d very different from 1, and increasing d to infinity tends to make the ratio closer to 1. In fact, the closer the viewing distance, the higher the influence of the 3D aperture problem, as is reflected in lower values of $\cos\varphi_\theta / \cos\varphi$ for each stimulus point.
(3) The compensation necessary to have no illusory effect would be reduced when the expansion/contraction speed was slowed, because the aperture problem (both 2D and 3D) could be solved possibly by larger receptive fields in higher visual cortical areas or by the propagation of the signals from the end-stopped neurons. Although this is not captured in the current version of the model, we can measure what a fraction of the fully predicted distortion can be achieved by each speed.
(4) If the visual system is not able to at least partially solve the aperture problem, the maximum compensation – based on inverting the distortion factor – would be the correct one to cancel the illusion. On the contrary, if a smaller amount of the predicted distortion is enough, it will demonstrate that the visual system can partially solve the aperture problem.

3.1.1. Methods

3.1.1.1. Subjects. Four naïve subjects (mean age 32 yrs; $SD = 2.7$) participated in the study. All had normal or corrected-to-normal visual acuity.

3.1.1.2. Stimuli. The stimuli were a series of movies with a physical distortion in the opposite direction of the perceived one, based on the simulations made by the Yazdanbakhsh and Gori (2011) model. Five levels of inverted curvature were applied, labelled 0 for no distortion up to 4 for distortion resulting from the full 3D aperture problem without even partial compensation by the visual system. To obtain level 4 of the opposite curvature, the distortion function of Eq. (4) in Section 3 is inverted (numerator and denominator replaced with each other). The opposite curvature (from Eq. (4)) is $1/f(n, x)$. To obtain k different levels of curvature, $k = [0, 1, \ldots, 4]$, we multiplied nv by weighted averages of the opposite curvature with no curvature ($f(n, x) = 1$). Thus at level k, the distortion factor was $nv\{[k/4f(n, x)] + (4 - k)/4\}$. The movies were prepared for 5 distances (d) from the screen: 15, 25, 35, 45 and 55 cm. As predicted by the Yazdanbakhsh and Gori (2011) model, the expected curvature of the stripes will be different. The size of the grating was always increasing from 9.4 to 9.8 cm. Fig. 8 shows few frames of the loop for the five nulling levels. For this example, the distortion made for 55 cm from the screen was used. Five speeds (v) were used: 1.2, 2.4, 3.6, 4.8, 6 mm/s.[1] Two different gratings were used: one with sharp boundaries and one with a Gaussian

[1] The five levels of speed in deg/s at the five distances from the screen are the following: At 15 cm: 0.46, 0.92, 1.37, 1.83, 2.29 deg/s; at 25 cm: 0.27, 0,55, 0.82, 1.1, 1.37 deg/s; at 35 cm: 0.2, 0.39, 0.59, 0.79, 0.98 deg/s; at 45 cm: 0.15, 0.31, 0.61, 0.76 deg/s; at 55 cm: 0.12, 0.25, 0.37, 0.5, 0.62 deg/s.

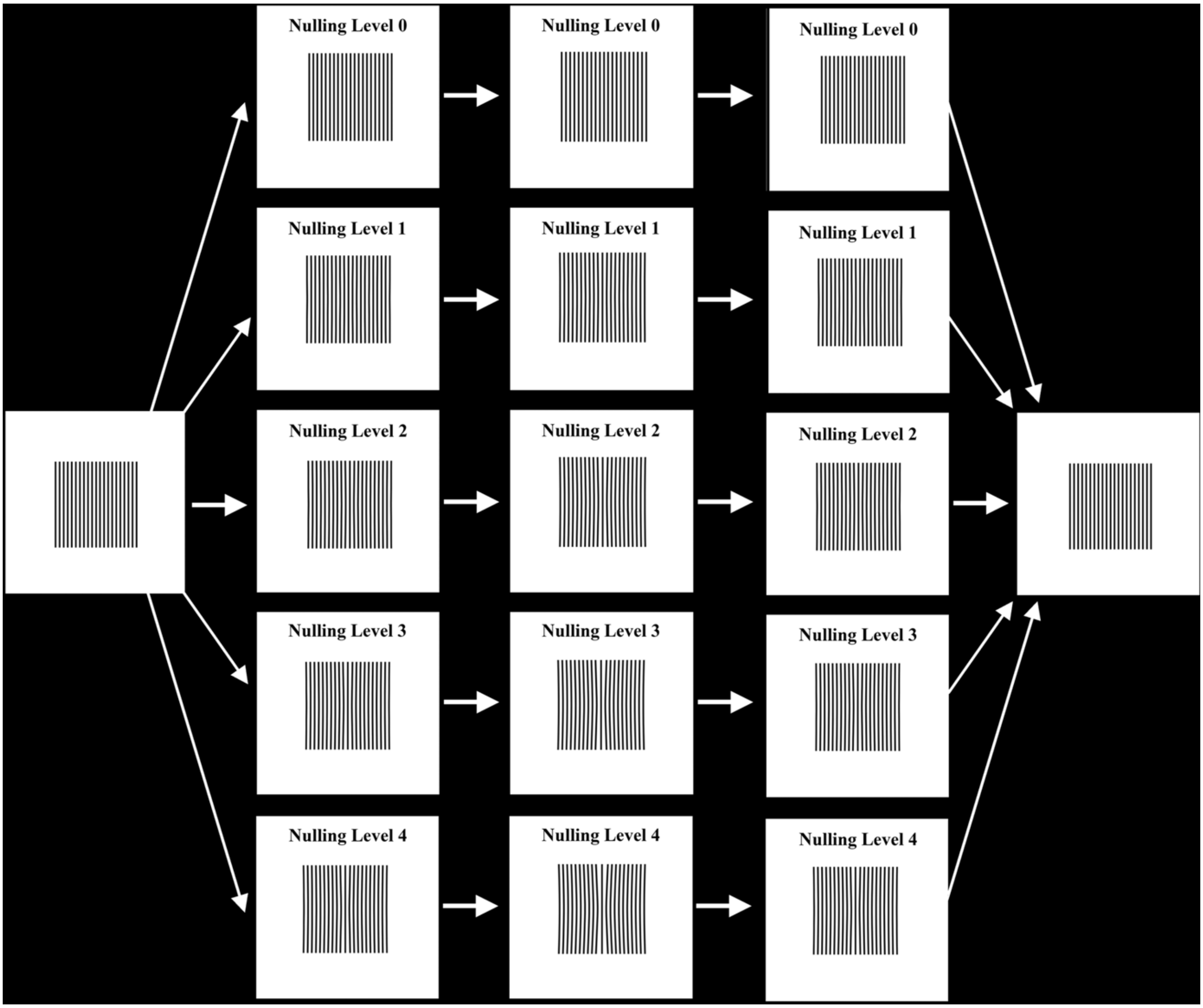

Fig. 8. A loop of expansion/contraction of the grating for the five levels of the nulling stimulus. With level 0 the physical curvature of the stripes was absent. As the nulling level is increased, the amount of curvature of the stripes is increased until it reaches its maximum for level 4. The subject has to choose at which level of distortion the grating appears as an expanding and contracting square (i.e. no curvature of the stripes is experienced).

blur applied. In total we used 250 movies (2 types of grating into 5 levels of physical counter curvature into 5 distances from the screen into 5 movie speeds).

A red fixation point was superimposed on the grating.

3.1.1.3. Procedure. The subjects at a fixed distance from the 28 × 21 cm monitor Sony Trinitron Color E100P looked to the series of movies characterized by different levels of physical counter distortion and they had to decide at which level of counter distortion the grating (that was expanding and contracting on the screen) did not show any curvature of the stripes. The subjects were instructed to perform the nulling task by focusing mostly around the central part of the stimulus. This is because the model described above is based on the assumption of full involvement of contour units without considering the end-stopped units that are definitely active at the line ends. As mentioned in Section 3.1, our analysis can best predict the distortion in the central part of the stimulus because the end-line signals are far enough to activate the end-stopped units. Thus, our calculation overestimates the curvature compensation in the peripheral regions close to line ends when they are not blurred. The subjects were allowed to go back and forward with the different movies until they were sure that this level of counter distortion creates the effect of an expanding/contracting grating without the curvature of the stripes. All the subjects did this task for both types of gratings, for all the viewing distances and for all the movie speeds. A chin rest was used to stabilize the head. The fixation was monocular.

3.1.2. Results

The results are summarized in Fig. 9. A repeated measures ANOVA with three factors (one for each dependent variable) was applied.

The extent of the compensation necessary to null the illusory effect was larger in the blurred patterns than in the sharp ones (Fig. 10) (one tailed $F_{(1,3)} = 5.598$; $p = .049$).

The amount of the reversed curvature necessary to null the illusory effect was significantly larger when the viewing distance decreased (one tailed $F_{(4,12)} = 43.778$; $p < .001$).

The illusory effect was almost absent when the movie speed was 1.2 mm/s and increased coherently with the movie speed (one tailed $F_{(4,12)} = 13.464$; $p < .001$).

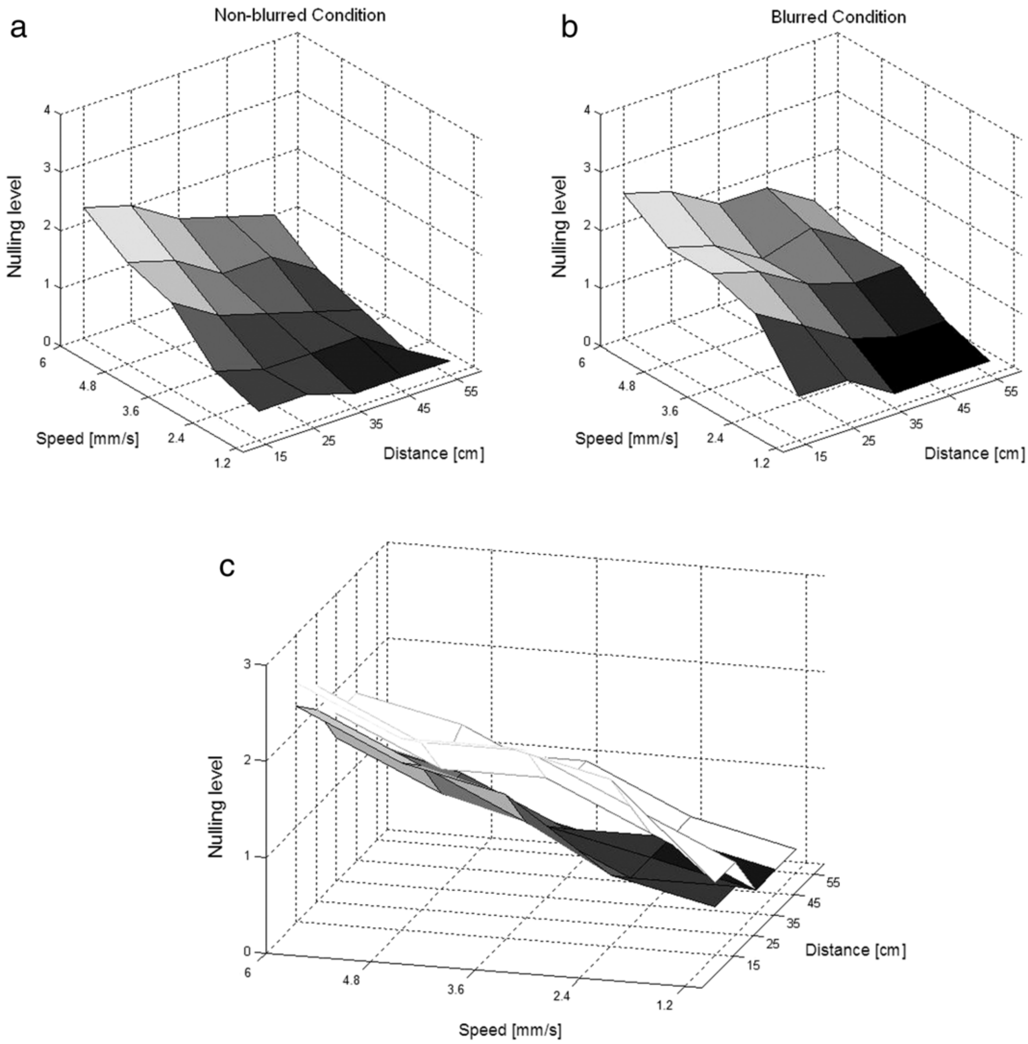

Fig. 9. Nulling experiment surface plots for blurred and non-blurred stimuli levels 0–4. (a) Non-blurred stimuli with higher level best null in the higher speed and closed distance. The same in (b). The superposition of surface plots in (a) and (b) shows the best nulling with overall higher level for blurred stimuli compared to non-blurred ones for almost each speed and distance in (c).

3.1.3. Discussion

The results generally support the predictions by the model and directly quantify the extension of the illusory curvature of the stripes at different speeds and distances from the screen.

The small difference between blurred and sharp stimuli might be a consequence of the instructions given to the subjects. The request to do the task only for the central part of the stimulus probably reduced the differences between the blurred and the sharp stimulus, because in both cases the contribution of the end-stopped neurons was reduced.

The variable ‘‘viewing distance’’ showed how the illusory effect changes as a function of *d*. Closer distances enhance the effect because the positioning of the projection line for each stimulus point imposes more 3D aperture effect.

The variable ‘‘speed’’ showed how an appropriate choice for movie speed is crucial to obtain the illusory effect that almost disappears at 1.2 mm/s. The results for this variable support the hypothesis that the integration processes (propagation of the end-stopped neurons signals and/or larger receptive fields in high cortical areas contribution) during the AGI observation requires time.

Finally, the inversion of the predicted curvature obtained by differential geometry based on the 3D aperture problem assumption is able to null the illusion but with less strength that was expected if the illusion comes only from the 3D aperture problem. It implies that the visual system somehow is able to partially correct the 3D aperture problem without fully ‘‘solving’’ it, in the sense that some residual distortion remains, but not so much as if the ‘‘full’’ 3D aperture problem resulted in a completely uncorrected percept.

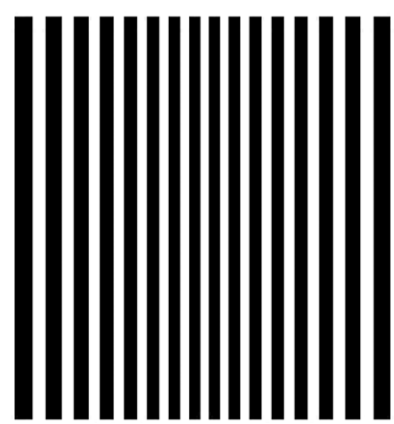

Fig. 10. A deformed version of the AGI that should minimize the contribution of the cortical magnification factor.

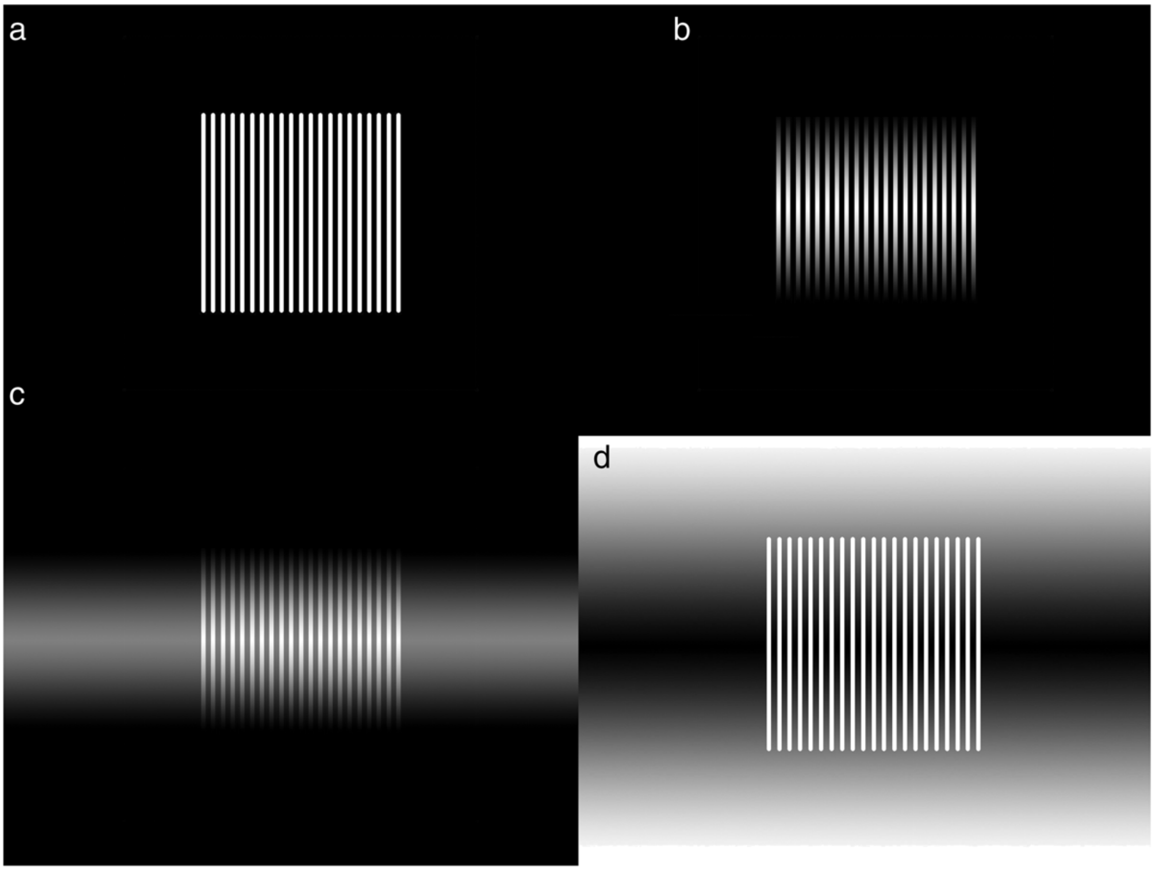

Fig. 11. These stimuli show how the blur itself instead of the difference in contrast seems to be responsible for the strongest illusory curvature presented in the blurred stimuli. See text for details.

In conclusion, testing of the model shows the aperture problem is partially compensated even in the conditions where the illusion is stronger. Our results suggest that the aperture problem is probably the main factor but not the only one involved in the illusion: other ambiguities or integrative processes seem also important to the resulted perceived distortion (Beck, Ognibeni, & Neumann, 2008; Caplovitz, Paymer, & Tse, 2008; Fantoni & Pinna, 2008).

4. Conclusions

We suggest that the main factor underlying the loss of a rigid aspect ratio for the striped pattern in the AGI is the classical (2D) aperture problem, which appears to underlie other motion illusions, including the Barber Pole (Wallach, 1935/1996), investigated by Lidén and Mingolla (1998), the Bressan–Vezzani (Bressan & Vezzani, 1995), the Bulging–Grid (Foster & Altschuler, 2001), the Revolving Wheels (Pinna & Brelstaff, 2000) studied by Gurnsey et al. (2002), and the RTLI (Gori & Hamburger, 2006), investigated by Gori and Yazdanbakhsh (2008).

The AGI has been here proposed as the simplest pattern that can highlight how the visual system fails to interpret the dynamical presentation of stimuli when the patterns' geometry presented to the early visual cortex receptive fields generates ambiguous and unambiguous motion signals.

The proposed models, in agreement with the electrophysiological results, seem to be appropriate to account for the two illusory phenomena offered by this pattern and to make predictions consistent with the experimental data. Further informal observations support the suggested explanation for this illusory phenomenon:

(1) Changing the fixation point changes also the direction of the illusory deformation, in agreement with the motion signalled by the contour units. For example, if the fixation is on the up left corner of the grating what it is experienced by an observer moving his head towards the stimulus is not an expansion of the grating but all the stripes move to the right, perpendicular to the stripe orientation.

(2) Another possible explanation for the dynamic deformation of the grating could be the cortical magnification factor (Daniel & Whitteridge, 1961). Approaching the AGI with central fixation only, the central part of the figure falls into the fovea where a very large number of neurons processes information for a small region of visual field. The rest of the grating is in the periphery of the visual field and is processed by a much smaller number of neurons. Fig. 10 is created to reduce the contribution of the cortical magnification factor while an observer approaches the grating, but, at the same time, it should not affect the aperture problem faced by the contour units. Moving back and forth, with central fixation, in front of Fig. 10 elicits a comparable illusory deformation presented in Fig. 1a. This observation minimizes the probability of a crucial contribution of the cortical magnification factor in the explanation of the AGI.

(3) Furthermore, superimposed after images due to motion could be considered an alternative explanation for the perceived deformation in the AGI. This explanation would predict perception of a superimposition of two gratings having different sizes as it showed in Fig. 4b in Anstis, Gori, and Wehrhahn (2007). This representation is far to what is perceived in the AGI.

(4) The strongest dynamic curvature observed in the blurred grating could also arise from the observation that stimuli with lower contrast are perceived to be moving slower than stimuli with higher contrast (Stone & Thompson, 1992). The velocity would be close to veridical at the stripe centre and slower than veridical at the edges. The blurred edges would seem to move slower due to lower contrast and strengthen the illusory curvature. If this is the main reason of the larger effect perceived in the blurred grating instead of the blur itself, a blurred grating presenting the same contrast with the background obtained by blurring the background as well (Fig. 11c) should result in a weaker effect than the blurred grating with a homogeneous background (Fig. 11b) and it should be comparable to the normal grating without blurred edges (Fig. 11a). Moreover, a sharp grating characterized by reduced contrast with the background at the stripe edges (blurring only the background as in Fig. 11d) should result in an illusory curvature stronger than the regular grating (Fig. 11a) and as strong as the blurred grating (Fig. 11b).

On the contrary, if the main reason of the strongest curvature effect is due to the reduction of the activity of end-stopped neurons due to blur, the grating in Fig. 11c should provide an equally strong effect as that in Fig. 11b and a stronger effect than Fig. 11a and d. As the reader can see moving the head back and forward with central fixation, the curvature effect is similar between Fig. 11b and c, and it is much stronger than in Fig. 11a and d.

It is interesting to note that Fig. 11c and d present also in their backgrounds an illusory variation in size and brightness already known as Breathing Light Illusion (Gori & Stubbs, 2006), which is due to the superposition of after images (Anstis et al., 2007; Gori, Giora, & Agostini, 2010). This effect should not distract the observer from the curvature effect that is the aim of this current study. The results of these observations support the idea that the blur itself and not the contrast variation is the main factor that strengthens the AGI. This is consistent with the results obtained here for the illusory expansion perpendicular to the stripes, where the blurred grating provides a stronger effect and also agrees with the stronger illusory rotation found in the RTLI for the blurred lines pattern (Gori & Yazdanbakhsh, 2008). In the last two cases, the reduction in perceived speed on the edges due to reduced contrast is not in agreement with the final percept.

In conclusion, we proposed here a new motion illusion presenting two illusory effects and we investigated these effects independently, proposing models that were successfully tested with empirical data. The nulling paradigms offered also a direct quantification of the two illusory effects and provided the contributions of the classical and 3D aperture problem for these phenomena.

Acknowledgements

We thank Sara Saba, who provided useful comments on an earlier version of the manuscript. E.M. was supported in part by the National Geospatial-Intelligence Agency (NMA201-01-1-2016) and the National Science Foundation (NSF SBE-0354378), Supported in part by CELEST, an NSF Science of Learning Center (SBE-0354378 and OMA-0835976).

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