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Asymmetry between horizontal and vertical illusory lines in determining the depth of their embedded surface

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Abstract

To investigate how the visual system integrates disparity information from horizontal and vertical edges and conveys it to the regions without any depth cues, we introduce a new phenomenon of subjective surface formation in an Ehrenstein-style configuration with inducing elements at different depths, and without explicit monocular occlusion zones. Different sets of experiments by separate groups of subjects suggest that when a subjective (illusory) square forms, it is at the depth of *vertical* illusory sides rather than *horizontal* ones. When the vertical side inducers are stereoscopically behind the horizontal ones, subjective surface formation is less likely. In depth assignment, we interpret the dominance of vertical sides over horizontal ones geometrically: vertical orientation can convey the horizontal disparity—a critical factor for Wheatstone (classic) stereopsis—but horizontal orientation per se lacks horizontal disparity information. Therefore, in the disparity integration, vertical illusory sides play a dominant role and their depth information influences the embedded subjective surface as well as the horizontal illusory sides.

Keywords: Depth capture; Illusory; Occlusion; Stereogram; Surface perception

1. Introduction

Disparity and occlusion are two important depth cues for our visual system. However, there are locations in the visual field without these cues, yet the visual system can assign depth to such locations. Illusory figures that lack visual information in their illusory parts are particularly useful in reflecting the visual system strategies for integrating visual information and conveying it to the illusory parts. In this article, the visual information of interest is depth. By the aid of illusory figures, we want to explore how local depth information is integrated globally and conveyed to the locations without any depth cue to generate a consistent 3D percept. Fig. 1 illustrates a well known example: A subjective square can form just by the presence of four discs with cut-out sectors. The cut-out sectors appear as the occluded parts of the black disks. The subjective completed edges of the square are called illusory contours and the white square in the middle is a subjective surface that has the discs with cut-out sectors as inducing elements or inducers. The figure-ground relationships lead to the interpretation that a white square with illusory contours occludes part of each inducing element, therefore the square is seen closer in *depth* than the inducers. Although the subjective square area (except the cut-out sector sections) lacks local occlusion or any depth cue, the whole area is assigned a unique depth in front of the corner inducers, illustrating that a few local depth cues are integrated and conveyed to the illusory parts. If two subjective shapes in Fig. 1 with crossed disparity are combined stereoscopically, the impression of near depth is enhanced and the clarity of the illusory contours increases. In this case, the crossed disparity reinforces the evidence

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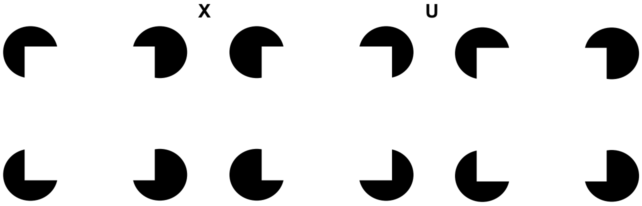


Fig. 1. If each half of the stereopair is viewed separately, it gives the impression that a subjective square stands on the four black disks. Crossed disparity of the vertical edges of the cut-out sectors enhances the impression of subjective square and its illusory sides (left pair for cross-fusers and right pair for uncrossed-fusers) and uncrossed disparity attenuates the effect.

of occlusion to give the impression of near depth to the subjective surface (Fig. 1). Local disparity cues in addition to the occlusion cues are integrated and conveyed to the illusory parts. On the other hand, in Fig. 1, uncrossed disparity attenuates the occlusion cue and makes the illusory contours less vivid (Gregory & Harris, 1974; Lawson, Cowen, Gibbs, & Whitmore, 1974; Ramachandran & Cavanagh, 1985). Ramachandran and Cavanagh (1985) explained the above phenomenon in terms of the depth capture of the subjective surface by the subjective contours: The white surface area within the subjective square does not have any local disparity information; only the inducers' disparity and occlusion cues influence the subjective square's depth (Watanabe & Cavanagh, 1992). In this regard, the phenomenon can be called depth interpolation between the illusory lines (Mather, 1989).

Aside from cut-out sectors as occlusion cues, another depth cue originates from the presence of the half-visible parts: The vertical edges of cut-out sectors have crossed disparity which also can be viewed as sections of each covered disk that is absent in the other half of the stereopair (Fig. 1). These half-visible parts are consistent with half-occlusion cues. Therefore, half-occlusion and disparity cues are not dissociable in Fig. 1. That means the investigation of disparity integration in such a stereogram inevitably introduces the integration of occlusion and half-occlusion cues.

We are interested in the integration of disparity information without being accompanied by half-occlusion cues. As before, the depth of the illusory parts reflects the integrated and propagated disparity information. The proper stimulus for this purpose has to have different disparity information that can be manipulated independently to observe the integration outcome. Independent manipulation of disparity direction is impossible in Fig. 1, because the horizontal and vertical edges of the cut-out sectors intersect (Fig. 2), hence any vertical edge disparity (that can also be interpreted as half-occlusion cue) is exactly equal to the horizontal edge termination disparity (which in the same way can be a half occlusion cue).

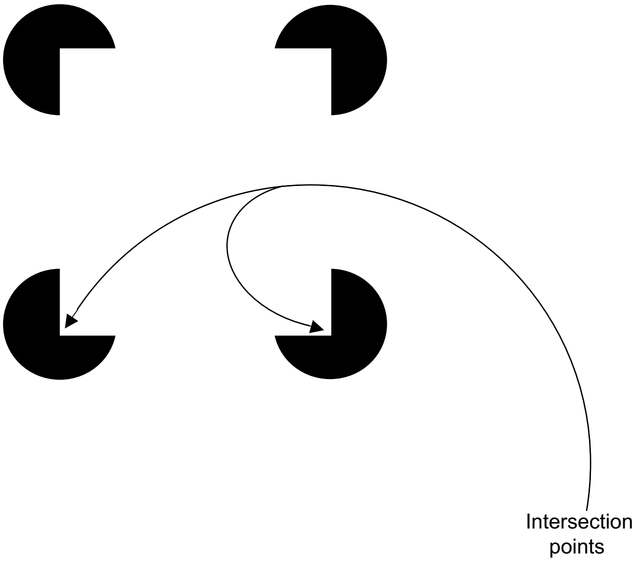


Fig. 2. The disparity of the vertical edges of the cut-out sectors can not be dissociated from the horizontal ones as they are solidly connected within the corner of the cut-out sectors and have a common intersection point. Therefore, any disparity of vertical edges of the cut-out sectors is exactly the same as the disparity of the horizontal edges' terminations. These disparities can also serve as half-occlusion cues which are linked together in the same way.

Therefore, to investigate the disparity integration, the geometrical property of Fig. 1 prevents independent manipulation of horizontal and vertical edges' disparity relative to each other and in addition to the disparity information, the stereogram in Fig. 1 also embeds the occlusion information in it.

Ramachandran (1987) rotated the stereopairs similar to Fig. 1 by 45° and implemented different disparity of cut-out sectors in top and bottom inducers compared to the left and right ones. Fusion of the resultant stereogram yields a folded square in depth. Therefore, the visual system interpolates different depth signals from different disparities (associated with half-occlusion cues) to generate a coherent depth percept. Although the stimulus used by Ramachandran allows independent manipulation of disparity, half-occlusion cues still accompany the disparity information. Therefore, to investigate different disparity integration without the presence of half-occlusion cues, another design is required. This requires changing the inducing elements such that these do not support the half-occlusion cues.

In Fig. 3, line inducers replace the corner inducers to generate a subjective square whose sides are no longer attached by corner inducers. Therefore, the relative disparity of vertical and horizontal inducers can be changed independently. The equal lengths of the vertical sides' inducers leave no half-visible part in the vertical sides' inducers: A condition which is inevitable in the corner inducer case.

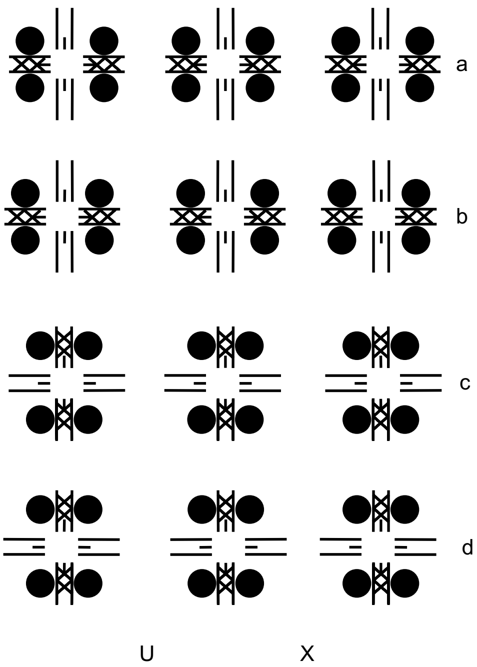


Fig. 3. Different conditions based on the relative disparity between horizontal and vertical inducers and the placement of the fusion complex (the parallel bars with crosses and circles over them) within vertical or horizontal inducers. Cross-fusers should fuse the right pair indicated by "X" and non-cross-fusers should fuse the left pair indicated by "U". In (a), the vertical side inducers (which are the fusion complexes as well) are nearer than the horizontal ones, and in (b) farther. The relative depth of horizontal and vertical inducers in (c) and (d) is similar to (a) and (b), respectively, but the fusion complex is switched into the horizontal inducers. These four conditions (two conditions for the relative depth×two conditions for the fusion complex to be within vertical or horizontal inducers) cover all possible permutations of stereogram components for the purpose of experiment.

We use the stereograms of Fig. 3 in the following experiment to investigate different disparity integration from different line inducers with different orientation by manipulating their relative positions.

2. Experiment: depth acquisition of square by its illusory sides

2.1. Observers

Two females and 10 males participated as observers. All had normal or corrected to normal visual acuity. The subjects were divided into the groups 1, 2, 3, and 4 with three subjects per each group to observe the stereograms a, b, c, and d in Fig. 3, respectively.

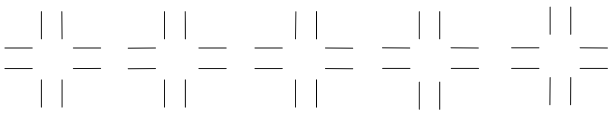
2.2. Materials

The stimuli were presented on a monitor (35°×27°, AOC 9 Glrs, 1152 by 864 pixel resolution) at 68.5 KHz horizontal and 84.9 Hz vertical frame rates, controlled by an AMD Athlon processor and viewed at a distance of 50 cm including the path of light through a mirror haploscope from the observer's eyes. The stimuli were generated and displayed with the Psychophysics toolbox (Psychtoolbox Win 2.50, Release 3), installed in MATLAB, version 6.0.0.88, Release 12.

2.3. Stimuli

Fig. 4 shows the four stereograms used in our experiments. The vertical and horizontal illusory contour inducers are aligned bar terminations. To facilitate binocular fusion, we added crosses and circles to either horizontal or vertical inducers, which are called from now on the *fusion complex*. To make sure that the results did not depend on the fusion complex being on horizontal or vertical inducers, each disparity relation has its fusion complex once on the vertical inducer in one stereogram and on the horizontal inducers in another stereogram. For example, in stereogram 4a the fusion complex is within the vertical inducers and in 4c it is within the horizontal inducers. The addition of the fusion complex serves as a fusion aid and replaces the omitted central fixation point. Removal of the central fixation point is especially important to avoid surface formation by depth propagation (Takeichi, Watanabe, & Shimojo, 1992). Takeichi et al. showed that if the relative depth of the fixation point in the middle of a subjective square was farther, then the fixation point depth would propagate within the illusory boundaries and enhance them to seem like occluding contours. Regarding the importance of the subjective surface depth for our present experiment, we have to avoid presenting the fixation point in the middle of the subjective surface, because it biases the surface depth when the fixation point is behind.

Fusion of stereograms 3a and 3c brings the vertical inducers in front of the horizontal ones; the two stereograms just differ with respect to the location of the fusion complex: within the vertical inducers in 4a and



a. Center **b. Right** **c. Left** **d. Down** **e. Up**

Fig. 4. Each illusory side of the middle square adjusts itself with the global grouping. The illusory sides per se do not have definite line terminations: in (a), the illusory line inducers have central symmetry. In (b), the rightmost pair of inducers is shifted to the right, which leads to the extension of the both horizontal illusory sides to the right. The same change but leftward in (c), downward in (d), and upward in (e) is depicted. These all show that this type of illusory line does not possess predetermined line ends and is adjustable within the global grouping to obtain its terminations.

within the horizontal inducers in 4c. The fusion complex in stereograms 4b and 4d follows the same pattern, respectively, however, after fusion the vertical inducers go behind the horizontal ones.

The luminances of the stimulus and background were 0.2 and 99 cd m^{-2}, respectively. Each half of the stereopairs was embedded in a virtual square of 5°×5°. The illusory square size is 1.25°×1.25°.

2.4. Procedure

In each trial subjects fused the two halves of the stereogram through a mirror haploscope.

The subjects' task was to report their percept in response to the questions which were asked in the following order:

1. What is the relative depth of the vertical and horizontal inducers?
2. Can a subjective square be seen in the middle?
3. If yes, is it folded in depth or flat?
4. If the subjective square can be seen, what is the relative depth of it with respect to the inducers?
5. Can a subjective edge be seen along the line ends of the top horizontal inducer?
6. If yes, is it like an occluding contour over the top inducer, or not?

Subjects from the beginning looked through the mirror haploscope without being exposed to the monocular images before.

We divided subjects into groups 1, 2, 3, and 4 to be tested separately by stereograms 3a, 3b, 3c, and 3d in order to make the reports about the surface percept reliable: if in one stereogram the subjective surface can be seen easily, and in the next one it is absent or unstable, then the same subject when presented to the next stereogram may give a mixed report, most probably because the exposure to the first stereogram biases the subject to report a square as a short-hand for a more complex (or hard to explain) percept of a partially complete grouping. To eliminate this effect, we used separate subject groups for each stereogram, and also did not expose the subjects to monocular images (which vividly induce the subjective square) before the main test.

2.5. Results

In response to question 1, subjects reported the relative depth of the vertical and horizontal inducers consistent with the relative disparity of the stereograms: Nearer depth for vertical inducers in stereograms 4a and 4c by groups 1 and 3 and farther in stereograms 4b and 4d by group 2 and 4, respectively (Table 1).

In response to question 2, the subjects of groups 1 and 3 (who were assigned to stereograms 4a and 4c) reported a subjective flat (question 3) surface at the depth of the vertical inducers in front of horizontal ones. The reported depth order (question 4) from near to far was a subjective square, vertical inducers infinitesimally behind, and the horizontal inducers more behind. One subject in each group reported a bistable percept (Table 1, groups 1 and 3). These subjects sometimes perceived the same subjective square with the same depth order and sometimes observed a clear depth difference between the inducers without any subjective surface. In these groups all subjects consistently reported the presence of a clear subjective and occluding edge along the line ends of the top horizontal inducers (questions 5 and 6).

Except for two bistable (flat) surface reports in groups 2 and 4 (assigned to stereograms 4b and 4d), the rest of the subjects did not perceive any surface (Table 1). In bistable cases, when the surface was perceived, the depth order report from near to far was horizontal inducers in front and subjective square at the

Table 1
Subjects reports about the depth order of inducers, presence of subjective square, and its relative depth with respect to inducers

Stereogram for each Group	Subject no.	Depth of vertical inducers	Subjective surface percept	Subjective surface depth
4a for group 1	1	Near	+	At vertical inducers depth (near)
	2	Near	+ (Bistable)	At vertical inducers depth (near)
	3	Near	+	At vertical inducers depth (near)
4b for group 2	4	Far	–	
	5	Far	+ (Bistable)	At vertical inducers depth (Far)
	6	Far	–	
4c for group 3	7	Near	+ (Bistable)	At vertical inducers depth (near)
	8	Near	+	At vertical inducers depth (near)
	9	Near	+	At vertical inducers depth (near)
4d for group 4	10	Far	+ (Bistable)	At vertical inducers depth (Far)
	11	Far	–	
	12	Far	–	

depth of flanking vertical inducers behind, like a square-shape hole being cut through the horizontal inducers. The rest of the subjects in the same groups described the clear depth difference of inducers without any surface in between, similar to the no-surface alternative in bistable cases. The weak and unstable percept of the top subjective edge (questions 5 and 6) in stereograms 4b and 4d looked like a contour over which the top (horizontal) inducer bars ended.

We summarize the subject reports as following:

1. The stable percept of the subjective surface occurs when the vertical inducers are nearer.
2. The stable and clear percept of occluding contour over the top (horizontal) inducer occurs when the vertical inducers are nearer. When the relative depth of the inducers reverses, this stable and clear percept switches into a weak and unstable illusory contour over which the lines of the top (horizontal) inducers end.
3. In all cases of subjective surface formation, whether bistable, stable, vertical inducers nearer or farther, the depth of the surface is at the depth of the *vertical* inducers, not the horizontal ones. When the surface is in front of the horizontal inducers, its top and bottom illusory contours seem like occluding contours. When the surface is behind the horizontal inducers, it seems to be cut-out through the horizontal inducers (as subjects explained it).

All of the subjects described the subjective surface like a bright square with no sharp corners.

3. Discussion

To address the integration of different disparities within different orientations, we studied illusory figures. Because the illusory parts lack disparity or other depth information per se, any subjective depth is the result of the disparity integration from real parts of the image, which is conveyed and reflected into the illusory parts. To make the independent disparity manipulation possible, we adopt line inducers instead of corner inducers.

The finding common to the above experiments is that the depth of the illusory square is captured by its vertical illusory sides rather than its horizontal ones, irrespective of whether the vertical inducers are the fusion complexes or not. Also in any surface-no-surface bistable percept, when the surface appears, it is at the depth of the vertical inducers.

This result shows in the formation of a subjective surface surrounded by vertical and horizontal illusory lines with different relative depths, our visual system assigns the depth of the vertical ones to the surface. Therefore, in disparity integration vertical side disparity has the dominant role compared to the horizontal ones. Notably, the subjective surface is not folded in depth to interpolate between different disparities, a phenomenon that can be seen in a variant of stereograms composed of corner inducers (Ramachandran, 1987), which have half-occlusion cues beside the disparity cues.

How can this finding be interpreted?

The disparity of corresponding projected scenic points on the retinas of both eyes is one of the cues used by our visual system for depth perception. Based on the location geometry of the eyes, which are separated *horizontally*, horizontal disparity becomes an important factor for depth cues. The optimum orientation to convey this horizontal disparity is *vertical orientation*. However, a real horizontal line or edge (which is not very long), has terminations that can convey disparity and give it an unambiguous depth. Eliminating the line terminations, omits local disparity-based depth cue; hence the global integration of depth information determines the final depth of the horizontal line.

Fig. 4a–e shows that an illusory horizontal contour induced by abutting line ends does not have any definite terminations; in other words, this type of illusory edge can have different terminations based on the global grouping of the image. For example, in Fig. 4b, the right illusory side is shifted to the right. As a result, the horizontal illusory edges extend to the right, too. The same can be done for the leftward, downward, and upward directions (Figs. 4c–e) to show the lack of terminations in this type of illusory contour and its dependency on emergent grouping. This explains why in disparity integration the vertical sides are dominant over the horizontal ones; the latter lack terminations to signal disparity.

Considering the illusory sides as the edges of the subjective square, our results show which illusory sides remain at their ‘‘initial depth’’ and which ones follow the emergent surface depth.

Here a new problem arises about the ‘‘initial depth’’ concept. It implies that illusory contours constructed by line ends’ abutment have a pre-assigned initial depth at the inducers’ depth, which can be modified later as the attached illusory contours of the subjective surface at the other depth. To address this problem, we need to test horizontal and vertical inducers separately. Fig. 5 shows the stereograms designed for this purpose. Four subjects (different from the subjects who participated in the main test) reported that the illusory contours and the subjective surface in-between were at the inducers’ depth, either when each half of the stereopair was seen separately or when the whole stereogram was seen through a mirror haploscope. In the main test, illusory contours were constructed by the same method (line termination abutment) and this pre-assigned initial depth hypothesis can be applied to them.

The other way to state our results is that horizontal illusory contours with no terminations have ambiguous

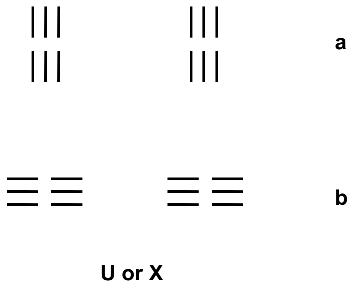


Fig. 5. Illusory contours connect the line terminations and embed a subjective surface between them at the lines depth, either when the illusory contours are horizontal (a), or vertical (b). In (a) and (b), the real inducers line are collinear as they are in the main test (Fig. 4). The control stereograms in (a) and (b) show that in such configuration, the subjective surface and its attached illusory contours are at the depth of their inducers. Four subjects besides the ones who did the main tests reported the same depth of surface, its illusory sides and inducers when observed these stereograms through a mirror haploscope. As the half-stereopairs are identical, they can be fused wither by convergence (X), or divergence (U).

depth, and based on their contribution in grouping at a specific depth plane, they are attached to that depth plane. Therefore, the ambiguous depth of the horizontal illusory contours without terminations is disambiguated by the depth of the grouped square which in turn has the same depth as its vertical sides. This experimental result is consistent with that part of FACADE theory (Grossberg, 1994; Grossberg & Howe, 2003), which mentions that the horizontal edges are added to all depth planes. Then in certain depth planes they can close a boundary. The surface feedback can fill-in successfully the closed boundary and form a visible (modal) surface. Then, the emergent surface with its supporting boundaries becomes visible at that depth plane, and all other horizontal boundaries in other depth planes that have not received filling-in surface feedback remain amodal (invisible). To make an analogy, in Fig. 3a, at near depth of the vertical sides, the square surface forms due to the presence of the depthless horizontal illusory sides that close the square boundary. Horizontal sides with initial far depth are invisible because they are not supported by any surface.

In this regard, the phenomenon of depth spreading mentioned by Takeichi et al. (1992) is relevant. In the present experiment, the inducer lines' terminations can be considered as the landmarks that "spread" subjective surface. Then our main question can be rephrased as: "Which line inducers are dominant factors for surface spreading? Horizontal inducers or vertical inducers"? The result that confirms the dominance of the vertical inducers also reveals "illusory contour enhancement" related to the "occluding contour formation", which was previously noticed by Takeichi et al. (1992). In their experiment, the crossed disparity of three dots within the subjective Kaniza triangle pushed the subjective triangular surface behind the 2/3 inducing circles (pacmen). Compared to the control stimuli without three dots, this enhanced the three illusory sides and made them look like occluding contours. In the stereograms of Figs. 3a and c, where the subjective square is in front of the horizontal inducers, the enhancement of horizontal illusory contours with the appearance of "sharp *occluding* contours" for their horizontal inducers is evident. This enhancement can easily be seen by comparing horizontal illusory edges in monocular images of Figs. 3a and c before fusing with binocular ones after fusing.

The other related phenomenon is the determination of subjective contours by the boundaries of the occluded rather than occluding regions (Gillam & Nakayama, 2002). In Figs. 3a and c, the subjective square is closer and can be considered as an occluder of the horizontal inducers. The near surface spreads until it faces the occluded parts (horizontal inducers) and does not spread beyond the occluded parts.

The present result is also consistent with the "common ground" phenomenon of He and Ooi (2000). They showed that the visual system may compute the depth of the image parts by comparing them with common surface to estimate the absolute depth. To confirm this, they noticed the perceived depth separation of two vertical parallel bars decreases if their top and bottom ends are connected by two horizontal lines. In their terminology, the visual system *underestimates* the slant of the resultant *common* enclosed surface and forces it to be on a frontal plane. Based on the idea of common surface as the reference frame for coding the object depth, the depth separation of the two vertical bars over this common surface is less. The vertical bar depths follow the slanted surface in parallel and the subjects underestimate their depth separation. In our experiments, another aspect of the common surface phenomenon can be seen: although the vertical and horizontal inducers in Fig. 3 are not in the same depth plane and no flat surface can pass through them, the visual system prefers to generate a unique flat common surface rather than a distorted concave or convex surface. In this way, the depth plane of the horizontal inducers is underestimated, while the vertical inducers generate the *common* surface. Notably, the generated common surface owns the horizontal illusory lines and the initial depth of the horizontal lines (based on the depth of their inducers) are underestimated. It is also consistent with He and Ooi (2000) finding that "perceived depth most likely occurs at the surface-representation level in visual system, when the visual surface has been explicitly delineated, rather than at the earlier disparity-processing level". The latter surface presentation level of He and Ooi (2000) is also consistent with FACADE theory (Grossberg, 1994) which states that the perceived depth of horizontal lines occurs after a successfully filled-in surface interaction with boundary system as mentioned before.

Anderson (1994) described horizontal and vertical image differences that are not disparities. These horizontal and vertical image differences signal the presence of local occluding contours, which have the strong tendency to interact cooperatively and form global contours. The global contours are not present in the monocular images. In fact *real* occluding contours can generate both horizontal and vertical image displacements that are due to the presence of half-occlusions, not binocular disparities (Anderson, 1994), the phenomenon that we avoided in our main stimuli. First, in our experiment there are no vertical and horizontal image differences in the sense noted in Anderson's work. There, each connected segment of the image has a vertical or horizontal difference equivalent to half-occlusion cue, but in our work, connected segments are exactly the same in each half of the stereopair, and no occlusion cue can be obtained in this way. Instead, only the relative positioning of inducers is different which causes a depth difference between the vertical and horizontal inducers based on disparity.

Another difference is that in Anderson's work (1994), the illusory contours are not present in the monocular images. Only after binocular fusion, partial occlusion cues give rise to a subjective surface in depth which borders appear like occluding contours. To the contrary, in our experiment, illusory contours are present in the monocular images at the depth of their inducers. After fusion, if the subjective surface forms, horizontal contours adjust their depth to the depth of the subjective surface and displace their initial depth.

Why is the subjective surface formation less likely when the vertical illusory sides are behind the horizontal ones? Perhaps it is then difficult to make any sense out of the configuration: the subjective square as a perceptually occluding surface (Gillam & Nakayama, 2002) cannot be behind the perceptually occluded inducers. These all show, in integrating the disparity information from horizontal and vertical orientations and conveying them to locations without depth information, our visual system follows the geometrical constraints and availability of depth data to determine the final percept.

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