

OCCLUSSION AND THE SOLUTION TO THE APERTURE PROBLEM FOR MOTION

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Abstract—The “aperture problem” indicates that a local reading of the velocity of an oriented contour is inherently ambiguous, insufficient by itself to recover the velocity of image points. In Wallach’s “barber pole” display consisting of moving diagonal lines within an elongated rectangular aperture, it has been suggested that the unambiguous motion of edge-terminators along the longer edges of the aperture propagates towards the motion-ambiguous center part of drifting stripes. This results in the perception of a surface moving in the direction of the longer axis of the aperture. By manipulating the stereoscopic disparity of a striped pattern relative to the aperture plane, we found that the disambiguating effects of terminators could be abolished if the striped pattern was in uncrossed disparity relative to the aperture plane. Also, the motion in 3 separate horizontally oriented, and vertically aligned apertures which would otherwise be seen as moving horizontally, was seen as “linked” together and moving vertically. This occurred only when the horizontally oriented segments separating these apertures were stereoscopically coded so that they appeared as occluders in front. These findings suggest that accidental or “extrinsic” terminators created by occluding edges are treated differently from real or “intrinsic” terminators, and that the real-world constraint of occlusion is thus implemented in the ambiguity-solving processes for motion.

Motion Aperture problem Stereopsis Occlusion Grouping Terminators

INTRODUCTION

Closer objects occlude more distant objects. Thus occlusion is a ubiquitous real-world constraint imposed on the visual input to our eyes. We have indicated that when objects are occluded, two kinds of surface boundaries are intermingled in the visual image; real object boundaries (intrinsic boundaries), and boundaries caused by another occluding surface in front (extrinsic boundaries) (Nakayama, Shimojo & Silverman, 1987, 1989b). The former serves as critical information for object recognition, whereas the latter varies depending on accidental, occlusive relationship among objects. We argue that the two kinds of boundaries need to be distinguished in order for the visual system to accomplish its goal of recognizing objects. Our study suggested that depth alone is sufficient for this distinction since common boundaries between two regions always belong to, or are attached to the front occluding region.

Figure 1, originally inspired by the demonstrations of Kanizsa (1979), illustrates how this

ambiguity is resolved so as to aid in the process of pattern recognition. When stereoscopic disparity or some other depth cue, such as an occlusion cue, indicates that the rectangular patch is in front of the curved object, the boundaries *X* and *Y* can be interpreted as occluding boundaries attached to the patch (Fig. 1A). For the purpose of recognizing the object behind, we argue that these extraneous boundaries, which are arbitrary and have no inherent relation to the rear object itself, should be “removed” or “subtracted” before the process of pattern recognition and the “C” is visible. Figure 1B illustrates the representation of the contours in the back plane after the “subtraction”, which is consistent with the “C” interpretation. In addition, information regarding depth and occlusion in the original image facilitates the correct “grouping” or completion of disconnected background blobs behind a closer object. If the occluder is made invisible leaving no indication of occlusion (as shown in Fig. 1C), all the boundaries will be treated the same, interpreted as inherent or intrinsic boundaries of the object(s). Such a contour representation is depicted in Fig. 1D. Thus, we spontaneously perceive the “C” in Fig. 1A,

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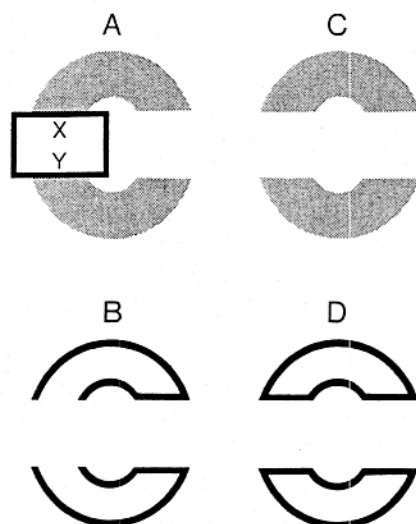


Fig. 1. Subtraction and grouping by occluding boundaries. In (A), a visible rectangle occludes the large letter C. If we assume that the horizontal bar is encoded as in front, then the common borders (*X* and *Y*) will be attached to the rectangle and detached from the letter C. (B) illustrates the contour representation in the rear depth plane after this "subtraction". If the occluder were to be invisible leaving no indication of occlusion as in (C), the boundaries *X* and *Y* can only be processed as intrinsic contours of the object, leading to a completely different percept. (D) shows the contour representation for the stimuli shown in (C).

whereas we perceive only u-shaped segments in Fig. 1C.

In the current paper, we report phenomena which suggest that a similar distinction of line terminators followed by subtraction/grouping procedures is also relevant for the perception of motion. This is of considerable interest because it puts the processing of "classification", "subtraction" and "grouping" prior to the solution of motion ambiguity, raising the possibility that such processes might occur relatively early in the visual pathway.

When a diagonal grating pattern is drifting behind a circular aperture, the direction of motion is physically ambiguous, as illustrated in Fig. 2A, although the perceived direction is usually orthogonal to the orientation of stripes. This is the well known "aperture" problem that has been explained in many studies (Wallach, 1935; Fennema & Thompson, 1979; Adelson & Movshon, 1982; Hildreth, 1984; Shimojo & Richards, 1986; Nakayama & Silverman, 1988a, b). Wallach's (1935) "barber pole" effect provides an illustration of solution to this ambiguity by showing that the shape of the aperture determines the perceived direction of motion. Thus, a vertically elongated aperture makes

vertical motion dominant (Fig. 2B), whereas a horizontally elongated aperture makes horizontal motion dominant (Fig. 2C). The perceived motion can sometimes fluctuate among several directions, but this is usually transient. Recent studies (Hildreth, 1984; Nakayama & Silverman, 1988b) suggest that this disambiguation may reflect the unambiguous motion detection of line terminators at the edges of the aperture, which in turn can propagate along the stripes towards the central part of aperture. Note that a vertical aperture, for instance, has longer edges at the vertical orientation, creating a larger number of terminators unambiguously moving vertically. Functionally, this mechanism ensures that we perceive the moving pattern as a rigid surface moving in one direction.

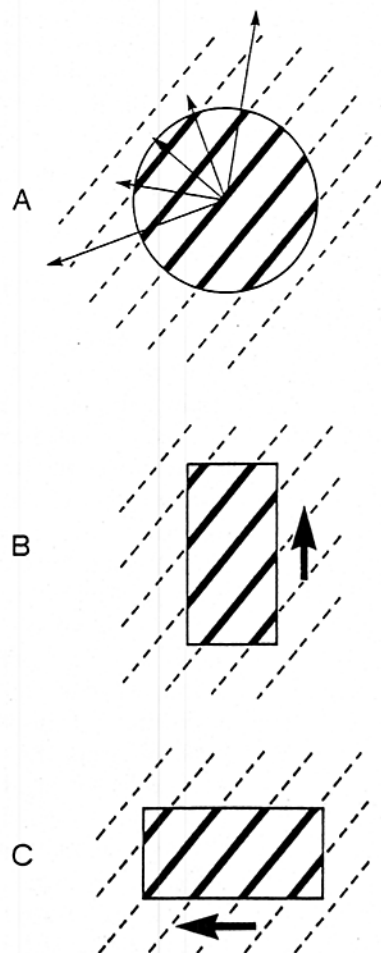


Fig. 2. The aperture problem and Wallach's (1935) "barber pole" effects. (A): ambiguity of motion in a aperture. (B) and (C): the "barber pole" effects. Perceived direction of motion depends upon the direction of elongation of aperture. Dashed lines refer to possible perceptual completion of invisible lines behind the aperture.

The explanation provided above treats terminators as the end points of a line. From our earlier discussion on occlusion and edge classification, however, it should be evident that the definition of the term "terminator" cannot be so straightforward because two kinds of terminator are intermingled in the visual image. Thus, in the examination of the ends of the diagonal lines in Fig. 2, we suggest that it is of major importance for the visual system to determine whether these are classified as "intrinsic terminators" which are inherent to the line themselves, or "extrinsic terminators" which are visible only by the accidental occlusion of these lines by an opaque surface.

In our study of pattern recognition (Nakayama *et al.*, 1987, 1989), photographs of human faces were sampled in horizontal strips and interposed with neutral strips. Such faces were much easier to recognize when the faces appear behind the strips than when they appear in front. We hypothesized that "classification" of boundaries, "subtraction" of extrinsic boundaries, and "grouping" of segmented image on the behind plane were involved in the underlying mechanism.

Quite similarly, we hypothesize that in the case of motion of diagonal lines moving in an aperture, classification of line terminators will take place. The differently classified terminators must have different effects in terms of "solving" the aperture problem. In particular, terminators should be identified as extraneous or extrinsic if they were encoded as behind an aperture and consequently "subtracted" such that they would have little effect in determining the perceived direction of motion of the whole surface (the "subtraction" hypothesis). When the moving lines are segmented into several subparts by intervening bars (Fig. 4A), extrinsic terminators should again be "subtracted". We also hypothesize that such lines are, at some level of representation, "completed" behind the occluder—a process analogous to "amodal" completion suggested by Kanisza (1979). As such, these separate segments should be integrated into a rigid whole surface moving in one direction (the "grouping" hypothesis). We argue that if the depth relationship is reversed so that the diag-

*Note that for the uncrossed case, this means that some portions of the grating in each eye will be binocularly unpaired, corresponding to those regions of the rear grating which are seen by one eye and not the other because of occlusion (see Julesz, 1971; Nakayama and Shimojo 1988).

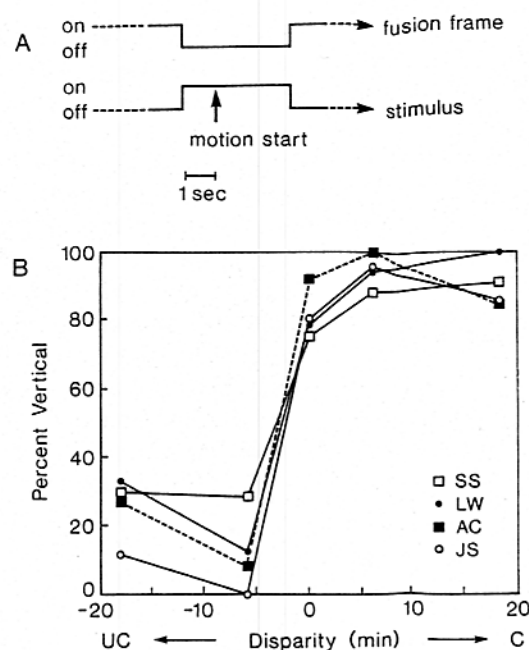


Fig. 3. Temporal diagram of stimuli and results of expt 3. (A): temporal diagram of stimulus. (B): results. The percentage of responses corresponding to vertical motion perception is plotted as a function of disparity for each of 4 subjects.

onal lines are seen as in front, no terminators would be identified as extrinsic, and no "subtraction" or "grouping" would be expected.

The "subtraction" and the "grouping" hypotheses will be evaluated separately (expts 1 and 3). In a subsidiary experiment (expt 2), we will also make a comparison between the binocular and monocular viewing conditions to understand the importance of generalized depth mechanisms, not specifically related to stereopsis, in the evaluation of occlusive relationships in the image.

EXPERIMENT 1: BARBER POLE EFFECT IS ABOLISHED IF THE STRIPES ARE SEEN AS BEHIND

Method

Our first experiment employed the same stimulus pattern as illustrated in Fig. 2(B) except that the stripes had one of the following five steps of disparity at the observation distance of 90 cm; 18 min uncrossed, 6 min uncrossed, zero, 6 min crossed, and 18 min crossed. The crossed and uncrossed gratings were constructed so as to mimic the real world situation where the observer viewed a diagonal grating either in front or in back.* The aperture is always oriented vertically and extended 1.2×3.3 deg

with a textured gray background (luminance; 33.8 cd/m^2). The background texture was correlated between the left and the right views at zero disparity. The spatial frequency, duty cycle, and luminance of stripes were 2.3 cpd, 0.17 and 111 cd/m^2 , respectively. The orientation of stripes was ± 40 deg with respect to the vertical. The velocity of stripes was 1.1 deg/sec (in the direction perpendicular to the stripes). The orientation of oblique, the direction of motion, and the disparity were all randomized from trial to trial. The stereoscopic display was created on a CRT display (Commodore Amiga 1000) using a mirror haploscope. Frame rate was 60 Hz.

A trial began with appearance of the stimulus pattern without motion for 1.0 sec, and then the stripes started drifting for 2.3 sec. During the interval between trials (7.3 sec), a pattern, which was identical to the zero disparity pattern except that there were no stripes, was presented to maintain the subject's fixation and fusion (see Fig. 3A for the temporal relationship of stimuli). The observers fixated on a reference point which was located just to the right (0.3 deg) of vertical aperture and always on during the experiment. The subject was asked simply to make a two-alternative, forced-choice judgment concerning whether the perceived motion was predominantly in the vertical direction (upward or downwards) or in the horizontal direction (leftwards or rightwards) at the time when the 2.3 second trial ended. 100 trials were ob-

tained from each of 4 subjects (including 2 naive ones who were well trained observers in stereoscopic experiments, but totally ignorant of the purpose and the predictions of the current experiment).

Results and discussion

Figure 3 shows the percentage of responses corresponding to "vertical" motion plotted as a function of disparity for each subject. As should be obvious from the figure, horizontal motion was dominant for the uncrossed disparity cases, whereas vertical motion was dominant for the zero and crossed disparity cases. Chi-square tests on the individual data revealed that there were highly significant differences between; (a) the uncrossed and the zero disparity conditions ($P < 0.005$ for all subjects), and (b) the uncrossed and the crossed disparity conditions ($P < 0.005$ for all subjects). The differences between the zero and the crossed disparity conditions were not significant except for one subject (LW; $P < 0.05$).

Thus, unlike the zero and the crossed disparity cases, which behaved in accordance with Wallach's (1935) original observations, vertical motion was *not* dominant even though there were a larger number of terminators on vertical edges of the aperture in the uncrossed cases.† This result is consistent with our "subtraction" hypothesis: line terminators which are created by occlusion are disambiguated and abolished at certain levels of visual processing so that they have little or no role in solving the motion ambiguity problem.

EXPERIMENT 2: ROLE OF MONOCULAR DEPTH CUES

The results in the zero disparity condition in the previous experiment deserve special mention. Here the barber pole effect works and this condition shows as strong a vertical dominance as in the crossed disparity case (Fig. 3). This may appear puzzling since one might have expected that these stripes would also be encoded behind the aperture by virtue of monocular occlusion cues (i.e. T-junctions). If depth is of so much importance in the distinction of line terminators, why is it that these monocular occlusion cues have no effect at all?

Further analysis of the situation suggests a possible explanation. In the previous experiment, the "barber pole" was viewed with both eyes. Thus in the zero-disparity case there is

†The percentage of "vertical" responses in the uncrossed conditions was considerably lower than the chance level (50%) (that is, the "horizontal" perception was more dominant than expected) in all the subjects. This may be explained by several factors. First of all, the oblique stripes at angles slightly closer to the vertical axis (± 40 deg) were biased in favor of horizontal motion because the vector perpendicular to the stripes was closer to the horizontal direction. Second, the subjects verbally reported that they observed an oblique, rather than vertical or horizontal, direction of motion more frequently in the uncrossed cases, which would be well expected if the disambiguating effects of terminators were suppressed as we had theoretically predicted. Further, there may have been some negative aftereffects or sequential contrast effects caused by overwhelmingly vertical perception in the zero and the crossed disparity trials which were randomly mixed with the uncrossed disparity trials. These contrast effects may have made the direction of motion more horizontal, either perceptually or cognitively or both. In fact, when tested *only* with the stimulus of 18 min uncrossed disparity in an additional experiment, the percentage of "vertical" responses increased in both of 2 subjects tested (from 30.0 to 45.0% in one subject, from 27.3 to 60% in the other).

Table 1. Results of expt 2. Percentages of responses corresponding to "vertical" motion are shown for both the monocular and the zero disparity conditions for each subject

Subjects	Monocular	Zero disparity	
SS	72.5	90.0	*
MP	35.0	47.5	NS
JS	45.0	77.5	**
KN	57.5	87.5	**

* $P < 0.05$. ** $P < 0.01$.

contradictory information. While monocular cues indicate that the stripes are in the back, the binocular system indicates that the diagonal lines are in the same depth plane, possibly overriding the monocular (T-junction) occlusion cues.

To explore this question, we ran the zero disparity condition again, comparing it with another block of trials where the display was viewed with one eye only. If our hypothesis is correct, then we might expect that the barber pole effect will be less pronounced in the monocular condition because monocular depth information will indicate that the stripes are indeed behind and this will not be cancelled by competing binocular information.

Method

Four subjects (including 2 naive ones) performed the same task as expt 1. From each subject, 40 trials were obtained under each of two viewing conditions: a monocular condition and a binocular, zero-disparity condition. Otherwise, stimulus parameters were the same as those in expt 1.

Results and discussion

As shown in Table 1, all subjects showed a lower percentage of "vertical" responses in the monocular condition relative to the binocular condition. This occurred even though there were individual differences in terms of absolute level of "vertical" scores. The difference was statistically significant for 3 of the 4 subjects ($P < 0.005$ for 2, $P < 0.05$ for 1, and not significant for 1 subject).

Thus, the effect of monocular depth cues on the solution of the motion ambiguity may be weaker than disparity cues, but they are not negligible. This result also implies that what is critical is not disparity information *per se*, but the depth information which can be carried by disparity or other cues.

EXPERIMENT 3: GROUPING "BEHIND" OCCLUDERS

Our second hypothesis, the "grouping" hypothesis, specifically predicts that 3 segmented apertures (as seen in Fig. 4A) can be integrated into an elongated larger aperture only if the regions in-between the apertures have crossed disparities relative to the aperture and the diagonal grating. According to our hypothesis, "vertical" perception of motion would be dominant only when the disparity of regions separating the small horizontal apertures is crossed relative to the aperture and the grating plane so that they appear in front. These regions are labeled "a" and "b" in Fig. 4A.

Method

The horizontal, textured bars "a" and "b" had either an uncrossed (18 min), a zero, or a crossed (18 min) disparity relative to the aperture and the grating pattern. The stimulus parameters and procedures were the same as those in expt 1 except that: (a) each of the 3 horizontal

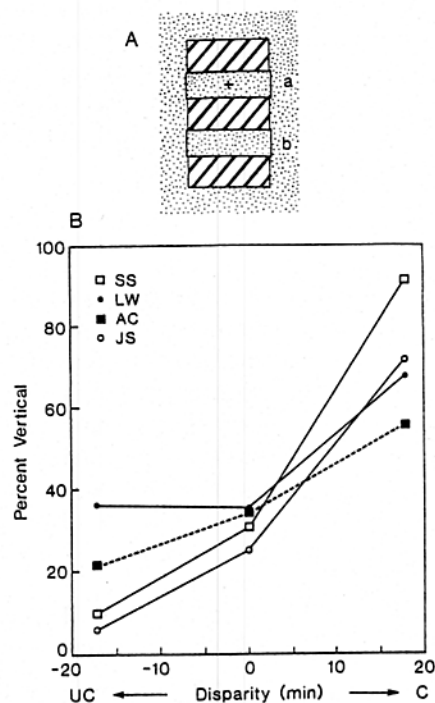


Fig. 4. The stimulus and results of expt 3. (A): the drifting stripes and the background have the same horizontal disparity, whereas two horizontal regions (a and b) had a disparity relative to them so that they appeared either in front of, the same depth as, or behind the stripes. A fixation point was added at the center of the region a. (B): results. The percentage of responses corresponding to vertical motion perception is plotted as a function of disparity for each of 4 subjects.

apertures were 1.2 deg high and 3.2 deg wide. The regions separating the apertures were 1.0 deg high; (b) the duration of motion was 3.3 sec; (c) 90 trials were obtained from each subject; and (d) the interval between trials was 5.6 sec. The same 4 subjects as in expt 1 participated. (The two naive ones were still uninformed of the purpose and the predictions of the experiments until they finished all the trials.)

Results and discussion

Figure 4B shows the obtained percentage of "vertical" motion perception as a function of disparity for each of 4 subjects (including 2 naive subjects). χ^2 tests revealed that there were highly significant differences between the uncrossed and the crossed disparity conditions ($P < 0.005$ for 2 subjects, and $P < 0.01$ for the other 2). There were also significant differences between the zero and the crossed disparity conditions ($P < 0.005$ for 2, and $P < 0.01$ for 1 subjects) except for 1 subject (AC). Unlike these, comparisons between the uncrossed and the zero disparity conditions revealed only marginal, if any, differences ($P < 0.05$ for 2, and not significant for the other 2 subjects). Thus, the results were highly consistent with the theoretical predictions of the "grouping" hypothesis.*

GENERAL DISCUSSION

We have shown that the resolution of motion ambiguity can be reversed simply by reversing interocular disparities, leaving spatio-temporal features of stripes and terminators unchanged. Our results show that when terminators are classified as "extrinsic" rather than "intrinsic", the dominant direction of motion can violate the simple "barber pole" law. Motion in the direction of longer axis is no longer dominant.

Adelson and Movshon (1984) have reported effects of disparity on the ambiguity solving process of motion, but in a very different paradigm. They found that when two sets of sine-wave grating were oriented and drifting in different directions, the "coherent" motion of

the resulting plaid in the direction predicted by the intersections of the two constraint lines is perceived only when the two moving patterns were in the same disparity plane. When the two patterns were in different depth planes, they were perceived separately as moving in different directions. This might suggest that the implications of our results may be essentially the same as theirs. Yet, it should be clear that the mechanism underlying Adelson and Movshon's phenomenon is very different because their results are unrelated to the issue of occlusion, and do not show nor do they account for the large asymmetry between crossed and uncrossed disparities reported here.

It is generally assumed that the ambiguity solving processes is fed by the direct outputs from early motion detectors. For instance, Movshon, Adelson, Gizzi and Newsome (1986) found that about 20% of the MT neurons respond to the direction of unitary motion of the plaid ("pattern direction-selective"), whereas V1 neurons respond to the directions of oriented grating components of the same plaid. Other studies are also consistent with this view (Albright, 1984; Maunsell & Newsome, 1987; Hildreth & Koch, 1987 for reviews). In addition Hildreth (1984) as well as Poggio and Koch (1985) have proposed a computational model of a possible biological mechanism. Both computationally and psychophysically, however, the aperture problem has thus far been considered mostly as a motion-only problem, where it has been tacitly assumed that motion "module" is encapsulated and distinct from other cortical processing "modules" (e.g. Marr, 1982).

Our results, however, suggest a more complex interaction, showing that depth information has a control over this particular level of motion processing, through a process which disambiguates *intrinsic* terminators and *extrinsic* terminators. This is not inconsistent with the latest anatomical/physiological mapping of visual pathways, in which motion and stereo functions share common visual pathways (Zeki, 1978; Van Essen & Maunsell, 1983; Livingstone & Hubel, 1987a, b; Hubel & Livingstone, 1987).

We argue, more specifically, that strong velocity propagation along lines are triggered by real (intrinsic) terminators, whereas the possible propagating effect of the occlusion-caused (extrinsic) terminators are abolished. Since MT seems to be responsible for at least some aspects of the ambiguity solving for motion, and we showed that depth-related processes are neces-

*It would be interesting to see whether similarity among motion segments in terms of spatial structure and velocity is correlated with the strength of "grouping" or "linkage". Our preliminary observations suggest that similarity is in fact a determining factor.

sary for the classification of terminators, it is not inconceivable that this classification can take place prior to MT, perhaps as early as V1 or V2. In particular, it is possible that our notion of terminator could be related to the "end-stopped (end-inhibited) cells", originally described as hypercomplex cells by Hubel and Wiesel (1968) and commonly encountered in striate as well as extrastriate cortex (Gilbert, 1977; Burkhalter & Van Essen, 1986). Our results indicate that if such "end-stopped cells" serve as the basis for line-termination, they would require more specific properties in relation to stereoscopic disparity, ones that have yet to be investigated. We suggest that disparity-specific cells could have highly selective inhibitory or blocking effects on end stopped cells. Thus, such end stopped cells might be suppressed when the regions at their terminators are coded as having crossed disparity and coded in front. It is only when there is no indication that the line is continual behind an occluder that such an "end stopped" cell would fire.

It should be recognized, however, that the analysis of occlusion could also occur at a higher level of analysis, yet influence motion processing at a lower level. Back projections from higher cortical areas are a very prominent feature of cortical anatomy (Van Essen & Maunsell, 1983) and, thus, the possibility of a "higher" to "lower" flow of information cannot be neglected.

The current findings, together with other recent findings from our laboratory concerning the asymmetrical effects of crossed and uncrossed disparities on face recognition (Nakayama *et al.*, 1987, 1989b), "neon" color spreading (Nakayama, Shimojo and Ramachandran, 1989), apparent motion (Shimojo and Nakayama, 1989), and the perception of monocular regions in stereograms (Nakayama & Shimojo, 1988), underscore the role of depth mechanisms in various aspects of visual information processing. We have recently reported the "slit motion phenomenon" which also demonstrates close interactions between depth and motion mechanisms (Shimojo, Silverman & Nakayama, 1988). And thus, they exemplify the implementation of early visual processing which is highly adaptive in relation to occlusion-related constraints in the real world.

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