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A NEW VARIANT OF THE BARBERPOLE EFFECT: PSYCHOPHYSICAL DATA AND COMPUTER SIMULATIONS

Dejan Todorović[1]
Laboratory for Experimental Psychology,
University of Belgrade, Serbia, Yugoslavia

The classic barberpole effect shows that perceived direction of motion of parallel line segments depends on the orientation of the frame defined by segment end points. A stimulus configuration was created by crossing two oblique barberpoles. Perceived motion in the crossed portion of the configuration is bi-stable, alternating between two oblique directions defined by the two component barberpoles. Ratings of dominance of perceived motion direction in the crossed portion of two barberpoles of different width and orientation revealed a strong preference for the wider component barberpole and a weak preference for the nearer-to-vertical component barberpole. A network model is presented in which each unit inhibits units with different direction sensitivity and co-extensive receptive fields, and excites units with equal direction sensitivity and neighboring receptive fields. Simulations of the temporal evolution of the spatial activity profile exhibit the effect of barberpole width and the bi-stability of percepts. Fatigue of highly adapted units enables the gradual emergence of non-adapted units. Small initial variations can lead to profound differences in the final state of the system, explaining the quasi-random fluctuation between the two perceptual variants.

Key words: *barberpole effect, bi-stable motion percepts, network model*

The barberpole effect is a motion perception phenomenon which shows that perceived motion direction may depend on global configurational aspects of the stimulus (Guilford, 1929; Wallach, 1935, 1976). Figure 1 depicts one way of demonstrating this effect. The objective direction of motion of line segments visible through the aperture is vertical; however, the perceived direction of motions is

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[1] Author's address: dtodorov@f.bg.ac.yu

oblique, that is, parallel to the path of segment end points. This effect was used as a test case by several computational motion models (Bülthoff, Little & Poggio, 1989; Hildreth, 1984; Marshall, 1990; Todorović, 1991, 1993; Waxman & Wohn, 1988). However, experimental studies of the phenomenon are still sparse. Thus in order to test more thoroughly the adequacy of these models, more empirical data are needed. This paper reports a study involving crossed barberpoles. The obtained effects are qualitatively explained through simulations of a model introduced by Todorović (1991).

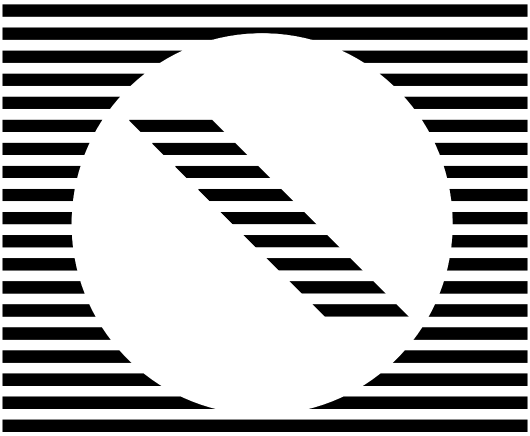

Figure 1: A set of parallel horizontal lines is translating vertically upwards. In front of the lines there is an opaque circular disk. An aperture in the form of an oblique parallelogram is cut out of the disk. The perceived direction of motion of the lines visible through the aperture is oblique.

In order to study the effects of aperture shape on perceived motion direction, I have used a crossed barberpoles stimulus. Imagine that in Figure 1 another oblique parallelogram is cut out, symmetrical with respect to the first. One obtains an X-shaped aperture (Figure 2), which can be described as consisting of two components, the NW (north-west bound) barberpole, an oblique parallelogram extending form bottom right towards top left, crossed with NE (north-east bound) barberpole, extending from bottom left towards top right. The two barberpoles are crossed, that is, they share a common diamond-shaped region.

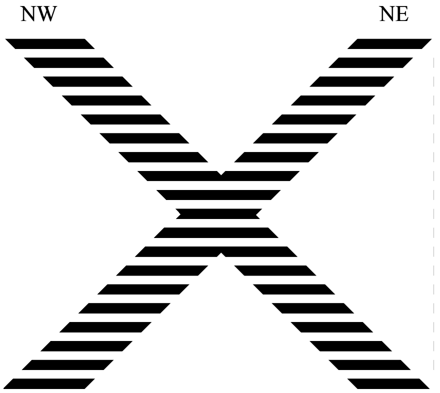

Figure 2: The crossed barberpoles.

Initial observations of this configuration indicated the following. When horizontal lines are moving vertically upwards in such an aperture, the precept corresponding to the uncrossed portions of the component barberpoles is in accord with the classical effect: the perceived direction of motion is parallel to the oblique sides of the components. Similar percepts were reported in a related stimulus configuration, by Watanabe & Cavanagh (1991).

In the crossed portion, the percept of the direction of motion is often initially unclear. With continued viewing, usually an oblique motion percept is established, appearing in one of two varieties, depending on whether the NW or the NE barberpole is perceptually prevailing (Figure 3). In either case, one perceives a continuous, uninterrupted oblique motion path, throughout the whole extent (crossed and uncrossed) of the perceptually prevailing component barberpole. The motion percept in the other oblique direction is confined to two separated segments of the uncrossed portions of the non-prevailing barberpole. The two motion paths are segregated by subjective contours, denoted by the dotted lines in Figures 3a and 3b. A small 3-D effect can be also noted, as the prevailing barberpole is perceived to lay somewhat above or in front of the other one, similar to a bridge over a river, viewed from above.

Prolonged viewing of the stimulus revealed that the percept is bi-stable: perceived motion in the crossed portion switches from one oblique direction to the other, making the previously prevailing barberpole non-prevailing and vice versa. The fluctuation of the percept has the classical features of multistability (Attneave, 1971): the two percepts are mutually exclusive; the restructuring of the percept is sudden; it occurs quasi-randomly, but it can be, to some extent, influenced by will. Similar reversals are reported, between vertical and horizontal perceived motion, when oblique lines are moving behind a square aperture, forming a 'square barberpole' (Wallach, 1935, 1976).

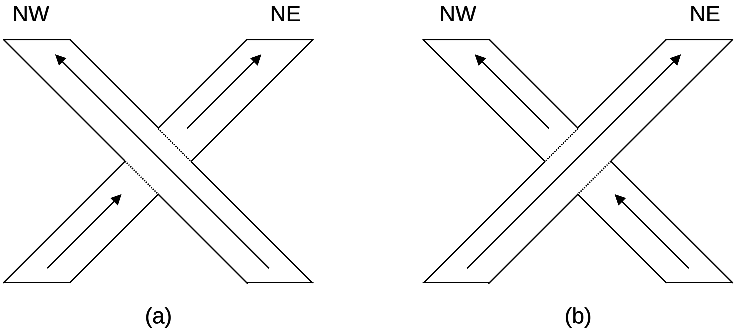

Figure 3: Two arrows indicate the direction of the motion percept: (a) Northwest prevails. (b) Northeast Prevails.

The two component barberpoles of the stimulus in Figure 2 are geometrically symmetrical. They are also perceptually equivalent, in that phenomenally, over an extended period of time there appears to be no obvious preference of one or the other of the two possible perceived motion directions in the crossed portion. However, initial observations suggested that in asymmetrical stimulus configurations one perceived motion direction in the crossed portion may dominate over the other. There are two ways to break the symmetry of the configuration in Figure 1. One is to vary the parameter of width (the length of horizontal cross-sections of component parallelograms), thus making one barberpole wider then the other. The other parameter is orientation (the angle of inclination of the parallelograms). In Figure 2, both barberpoles are oriented at 45^0 with respect to horizontal, the NW barberpole clock wise, and the NE barberpole counter-clockwise. Changing this parameter makes one barberpole more inclined than the other. The effects of these two parameters on the perceived direction of motion in the crossed portion of the configuration were studied in an experiment.

EXPERIMENT

Method

Subjects: Four Belgrade University undergraduates participated in three sessions, held on different days.

Stimuli: Nine stimulus configurations were constructed, consisting of a fixed NE barberpole and a variable NW barberpole. The width of the NE barberpole was always 20^0 and its orientation was 45^0 counter-clockwise from horizontal. The NW barberpoles had widths of 10^0, 20^0, and 40^0 and orientations of 22.5^0, 45^0, and 67.5^0 clockwise from horizontal. The stimulus configuration fits into a rectangle whose vertical extent varied between 2.4^0 and 3.1^0, and whose horizontal extent varied between 2.9^0 and 3.9^0, depending on the orientation of the NW parallelogram. The top and bottom sections of both component barberpoles were horizontal. Objective motion direction of the squarewave grating was vertically upwards, with a speed of 0.29^0\sec. Its spatial frequency was 4.5 cycles\$^0$. Stimulus presentations were programmed in assembly language on an Apple IIe computer with accelerator. Image displacement was one pixel at time and perceptually smooth.

Procedure: A session consisted of randomly ordered presentations of each of the nine stimuli for 60 seconds, at a viewing distance of 230 cm. The experimental room was half-lit, in order to reduce the generation of afterimages. There was a 15 sec pause after each presentation during which the screen was blank. The subject were instructed to keep their gaze within the crossed portion of the stimulus figure. The task was to rate, on a scale of 1 to 5, the degree of dominance of the NE barberpole, taking into account the amount of time each direction of motion was perceived during the presentations, and how easy it was to intentionally switch from one percept to the other.

Results

The mean dominance ratings based on three sessions of four subject are presented in Figure 4. Note that a rating of 3 means that the two barberpoles are perceptually equally salient. The results show that this is what happens when both barberpoles have same width (20'). When the NW barberpole is thinner (10'), the NE path tends to dominate (ratings of 4 and higher), and vice versa. The effect of width was significant: $F(2,6) = 56.51$, $p < 0.001$. The main effect of orientation was not significant, but there was a significant interaction of width and orientation: $F(4,12) = 3.51$, $p < 0.04$. This was due to the absence of simple effects of orientation for the 10’ and 20’ NW barberpoles, but the presence of this effect for the 40' NW barberpoles: $F(2,12) = 17.09$, $p < 0.001$, for which the dominance of the NE path decreased with increased vertically of the NW path.

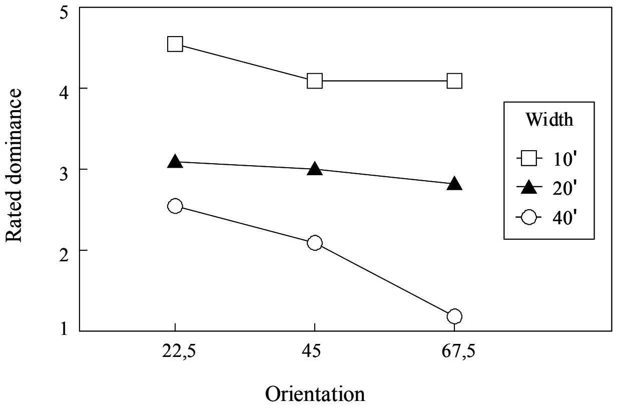

Figure 4: The mean dominance ratings of the NE barberpole as a function of width and orientation of the NW barberpole.

Model

The classic single barberpole effect indicates that motion signals form the contours may decisively affect the motion percept within the interior of figure. The dominance of contours in this motion perception phenomenon is analogous to the well known contour effects in brightness and color perception, such as the brightness and color contrast, the Koffka-Benussi ring, the Craik-O'Brien-Cornsweet effect, and others (Grossberg & Todorović, 1988). In a previous paper (Todorović, 1991) I have introduced a simple model of perceived motion of dotted lines in the standard single barberpole configuration. In the present paper, it will be shown how that model can explain the percepts in the crossed barberpole configuration.

Architecture

In this mode, perceptual effects are assumed to directly depend on the activity profile of a sheet of hypothetical neural units, termed 'the motion layer', tentatively identified as critical area MT. Such units receive their inputs from three sources. First, bottom-up inputs which refer to the activation of motion layer units by direction-of motion sensitive neurons, such as simple or complex cells of areas V1 or V2. Second, lateral inputs which are constituted by mutual excitatory and inhibitory interactions of motion layer units. Third, top down inputs, which are exerted by higher-order areas corresponding to voluntary decisions by the viewer to bias or alter the perceived motion direction. In the following, only the lateral interactions will actually be modeled; the structure of the other effects will be assumed on the basis of hopefully reasonable guesses.

The structure of lateral interactions was modeled after psychophysical studies of motion perception which suggest the existence of both excitatory and inhibitory connections between motion-sensitive units (Marshak & Sekuler, 1979; Williams & Phillips, 1987). The neural correlates of such interactions may involve horizontal connections between cortical neurons (Matsubara, Cynader, Swindale & Stryker, 1985; Ts'o, Gilbert & Wiesel, 1986). In the model, each small portion of the retina is assumed to be monitored by a local cluster, that is, a set of motion layer units with co-extensive perceptive fields, but with different directional preferences. The main design feature is that each unit is inhibited by other units within its cluster, and excited by other units from neighboring clusters with equal directional preferences. In the present implementation of the model, units with only three different directional preferences are included in simulations: they are denoted as *nw*-units (north-west reference), *n*-units (north preference), and *ne*-units (north-east preference). These geographical terms are not meant to imply environmental directions but are used only for denotational purposes. The architecture of the lateral interactions is depicted in Figure 5.

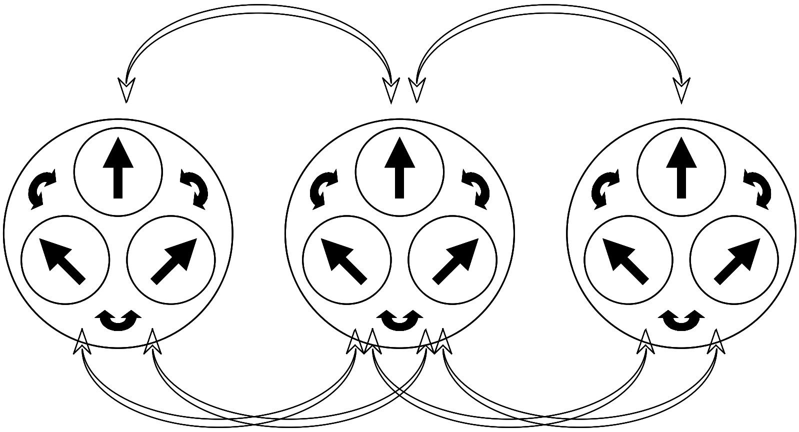

Figure 5: Three local clusters are represented with large circles. Each large circle contains three small circles that represent units with different directional preferences, symbolized with straight single-headed gray arrows (nw-unit, n-unit, and ne-unit). The small black curved double-headed arrows indicate inhibition of each unit within a cluster by the other units The large white arched double-headed arrows indicate excitation of each unit by units with the same directional preferences from neighboring clusters. In this figure, only two neighboring clusters of the middle cluster are depicted.

Equations

Let a unit from cluster *i* and direction preference *d* be denoted as $x_i^{(d)}$, and its activity level, at time *t*, as $A_i^{(d)}(t)$. In the present implementation of the model each cluster contains three units $x_i^{(ne)}$, $x_i^{(n)}$, $x_i^{(nw)}$, that is, *d* is a member of set D = {*ne,n,nw*}. At time *t* = 0 the activity level of each unit is set equal to its bottom-up input $B_i^{(d)}$. The structure of the bottom-up input will be described in the section on simulations. The activity level at time *t +1* is recursively defined in two steps. Briefly, in the first step an intermediate quantity called the total activity level is computed. In the second step, the new activity level is computed by normalizing the total activity level.

The total activity level $C_i^{(d)}(t)$ of unit $x_i^{(d)}$ at time *t* is defined as the linear combination of four components, the current activity level $A_i^{(d)}(t)$, the excitatory effect $E_i^{(d)}(t)$, the inhibitory effect $I_i^{(d)}(t)$, and the constant bottom-up input $B_i^{(d)}(t)$:

$$C_i^{(\mathrm{d})}(\mathrm{t}) = \tau \mathrm{A}_i^{(\mathrm{d})}(t) + \alpha E_i^{(\mathrm{d})}(t) - \beta I_i^{(\mathrm{d})}(t) + \gamma B_i^{(\mathrm{d})}$$

If total activation is negative, it is reset to zero. The weight parameters τ, α, β and γ reflect the relative sizes of the contribution f each component.

Let the excitatory set of $x_i^{(d)}$ (that is, the set of units with equal direction preference, belonging to neighboring clusters) be denoted as $ES_i^{(d)}$. The excitatory influence on unit $x_i^{(d)}$ is equal to the summed activity of units form $ES_i^{(d)}$:

$$\mathrm{E}_\mathrm{i}^{(\mathrm{d})}(\mathrm{t}) = \sum_{j \in ES_i^{(d)}} A_j^{(d)}(t)$$

Let the inhibitory set of $x_i^{(d)}$ (that is, the set of units with different direction preferences, belonging to the same cluster) be denoted as $IS_i^{(d)}$. The inhibitory influence is equal to the summed activity of units from $IS_i^{(d)}$:

$$\mathrm{I}_\mathrm{i}^{(\mathrm{d})}(\mathrm{t}) = \sum_{j \in IS_i^{(d)}} A_j^{(d)}(t)$$

The new activity level of unit $x_i^{(d)}$ at time $t + 1$ is given by the normalized total activity level:

$$\mathrm{A}_\mathrm{i}^{(\mathrm{d})}(\mathrm{t+1}) = \mathrm{S} \cdot \frac{C_i^{(d)}(t)}{\sum_{d \in D_i} C_i^{(d)}(t)}$$

where, as defined above, D_i denotes the set of all motion direction preferences in cluster i. The operation of normalization is computationally convenient because it keeps the sum-total activity level within a cluster equal to S. For more detailed technical information about the model, the pervious paper (Todorović, 1991) may be consulted.

Simulations

The following three figures depict simulations of the activity level profile of 147 motion layer units organized in 49 local clusters, stimulated by a crossed barberpoles configuration which the NE parallelogram is wider than the NW parallelogram. In these figures, each motion layer unit is coded by a line. Line position is determined by the location of the local cluster to which the unit belongs. Line orientation codes unit direction preference (*ne, n,* or *nw*). Line length (which may be zero) codes activity level magnitude of the unit at the given temporal cycle. Each local cluster is represented by up to three crossed lines. The top figure in each simulation represents the state for the system, that is, the activity levels of all units at time t = 0. The following three figures in each simulation represent the state of the system at several chosen iteration cycles. The values of the promoters were τ = 0.9, α = 0.4, β = 0.3, γ = 0.2 and S = 1. One version of the simulation program presents the iteration cycles in quick succession, to that the temporal evolution of the system can be observed on the computer screen.

Simulation 1: unambiguous motion and effect of width

Figure 6a shows the assumed initial state of activity (t = 0) of the motion layer units when the visual system is stimulated by the crossed barberpole configuration. It depicts the hypothesized effect of the bottom-up input, before the influence of lateral effects has begun to set in. Note two types of cluster activity structure. First, at the locations corresponding to the edges of component barberpoles, a single unit is active, whose motion direction preference coincides with the unambiguous path of segment end-points. The magnitude of the activity level is equal to the normalization constant S. Second, at the locations corresponding to the interior portions of segments, all three cluster units are active. This type of structure reflects the aperture problem (Adelson & Movshon, 1982; Hildreth, 1984; Marr & Ullman, 1981; Stumpf, 1911; Todorović, 1991, 1993). A vertically moving horizontal line longer than the receptive field stimulates not only the *n*-units, sensitive to vertical motion, but also, to same extent, *ne*-units and *nw*-units as well. The initial activity levels of the two obliquely tuned units were set to 71% of the activity level of the *n*-unit, which corresponds to the cosine of 45^0. The sum of the three activity levels is equal to the normalization constant S.

A plausible structure of the percept corresponding to such a neural profile is as follows: at the edges, unambiguous perceived motion direction, parallel to the edges; in between the edges, relatively ambiguous motion percept, with a tendency for vertically upwards motion. However, this is not an adequate description of the actual percept. In the classical single barberpole stimulus, as well as in the crossed barberpoles configuration, the percept of motion direction is unambiguously oblique throughout the extent of the barberpole. Such an unambiguous structure of the percept, as well as the width effect in crossed barberpoles, can be explained by the action of lateral effects.

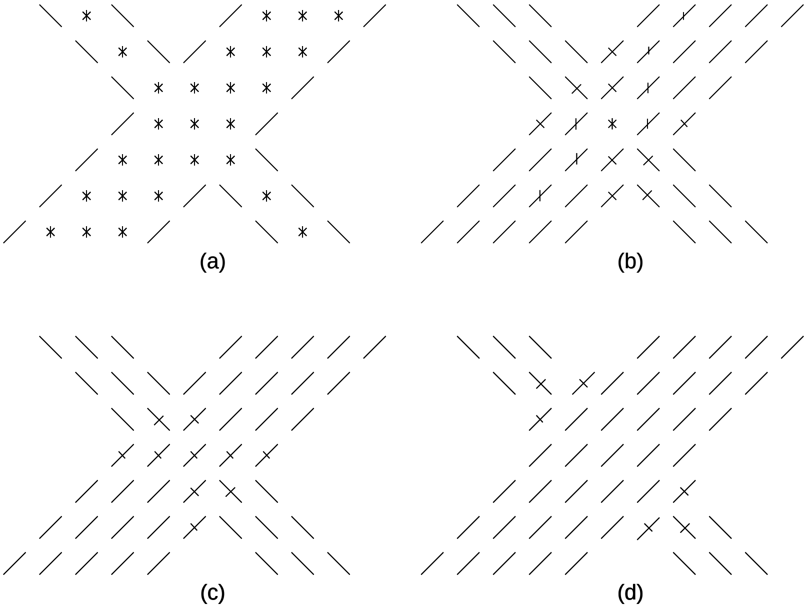

Figure 6: Unambiguous motion and effect of width. Iteration cycles: (a) 0, (b) 3, (c) 6, (d) 20.

The simulations in Figure 6b-d show how unambiguous motion information from the edges spreads toward the interior of the figure, quickly establishing fields of uniformly active units within the uncrossed portion of the stimulus. In the crossed portion of the figure, a competitive interaction of units with opposed motion preferences unfolds. This competition is eventually 'won' by the ne-units. In the final figure most local ambiguities are resolved, that is, most local clusters contain a singled wining unit. There is a continuos field of uniformly active ne-units, forming a NE path, corresponding to the wider parallelogram. This activity profile corresponds with the perceptual structure of the dominant percept for such a stimulus.

Simulation 2: the switch to the non-dominant percept

With prolonged viewing the motion percept in the crossed portion of the stimulus changes form one oblique direction to the other. This happens even if one component parallelogram is wider than the other, although the wider motion path tends to dominate, and it may take more voluntary effort on the part of the viewer to change the motion percept. I will argue in the following that these effects may be accounted for by adaptation, attention, and chance fluctuations.

There are well-known perceptual adaptation effects of prolonged exposure to optical motion, such as the motion after-effect in stationary stimuli, or change of perceived direction of moving stimuli (see Anstis, 1986). After adaptation to unambiguous vertical motion, the directional percept in Wallach's square barberpole tends to be horizontal (Redlsob, 1938). Such effects are generally thought to be due to neural adaptation of directionally sensitive cortical units (Peterson, Baker, & Allman, 1985; Vautin & Berkley, 1977).

The process of adaptation is not explicitly implemented in the present model. However, some of its effects can be assessed by the following considerations. Prolonged activity induces strong adaptation effects in the winning units. Because of the interactive architecture, the effects of adaptation are not confined to the decrease to the units' own activity level. The activity of the other units in the cluster increases due to decreased inhibition from the winning unit as well as to normalization. Furthermore, the facilitating effect of the winning unit on neighboring units also decreases, leading to further changes in the overall activity profile.

Selective attention can also exert influence on motion perception (Chaudhuri, 1990; Corbetta et al., 1990). The structure of the percept induced by multistable stimuli may be biased by the volitional effert fo the viewer. There are indications that the physiological correlate of attention is increased activity level of neurons coding unattended features (Spitzer, Desimone & Moran, 1988; Wise & Desimone, 1988).

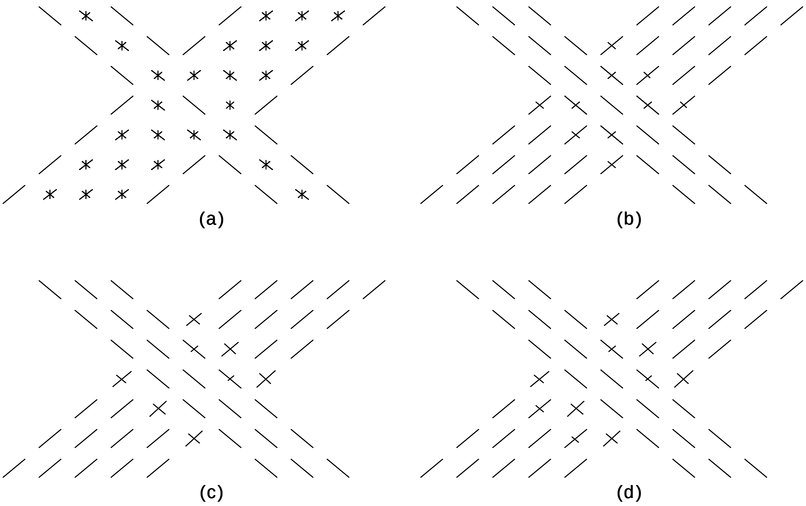

Figure 7: Switch to the nondominant percept.
Iteration cycles: (a) 0, (b) 10, (c) 20, (d) 30

Figure 7a depicts an example of a profile that incorporates the hypothesized effects of adaptation, attention, and chance fluctuation. Compared to figure 6a, adaptation is assumed to have reduced the activity level of many winning units, and to have indirectly increased the activity of units with other directional preferences. Chance fluctuations are assumed to have favored the activity of some *nw*-units located at the crossed portion. The effect of a top-down voluntary bias is represented by strong *nw*-unit activity in the cluster located in the middle of the display.

In figures 7b-d, temporal unfolding of lateral effects is simulated in the same iterative manner as in the previous set of simulations. The figures show how, due to the interplay of competition and co-operation effects, the initial activity profile develops into a state which, in contrast to the previous simulations, exhibit a continuos NW path, and discontinuous NE path. This profile corresponds to the non-dominant percept for such a stimulus.

Simulation 3: instability of transitional states

The reaction of the perceptual system to the crossed barberpoles, and many other bi-stable stimuli, can be described as an irregular oscillation between two quasi-stable attractor states. The states are quasi-stable because one percept eventually gives way to the other. The oscillation is irregular because the system spends most of its time in the two attractors, while the transition interval is short and occurs seemingly at random. The last series of simulations suggests that the unpredictability of exact moments of perceptual reversal is caused by chance fluctuations of local aspects of the system. Rather than being irrelevant quantitative noise, local fluctuation may decisively influence the global, qualitative characteristics of the motion layer activity profile.

Figure 8a is almost identical to Figure 7a. The difference is confined to a single cluster, located immediately below the center of the display, in which, in contrast to figure 7a, *ne* unit activity exceeds *nw* unit activity. This slight initial difference is enough to change the global course of the system, as shown in figures 8b-d. In contrast to figure 7, the NE path now prevails.

Effects similar to small fluctuations in unit activity are also exerted by small changes in interaction parameters. In Figure 7a, if the inhibitory parameter β is lowered from .30 to .25, the NW path continues to prevail; but, for $\beta = .24$, or if the excitatory parameter values appears to be restricted to unstable states of the system, such as Figures 7a or 8a. In Figure 6a, much larger variation of system parameters has no influence on the final state of the system. It remains an open question, how the boundary between states of the system that converge towards one or the other attractor depends on stimulus and system parameters, and whether it is well-behaved or perhaps fractal.

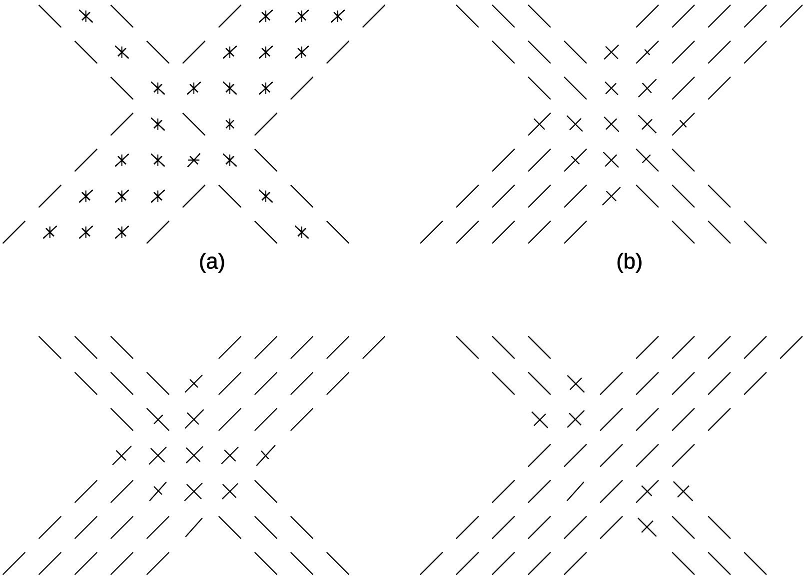

Figure 8: Instability of transitional states.
Iteration cycles: (a) 0, (b) 10, (c) 20, (d) 30

In conclusion, the model can qualitatively explain the effects of barberpole width on perceived notion direction, the switch to the nondominant percept, and the irregularity of the transition. The partial effect of orientation might be explained in a richer model containing units with more than three direction sensitivities. Another effect that the model currently cannot account for was shown by Watanabe & Cavangh, 1991: when a stimulus similar to Figure 2 is embedded into an Ehrenstein cross, the perceived direction of motion in both component barberpole is orthogonal to the orientation of the moving lines. This effect could be explained by the inhibitory influence of the Ehrenstein figure on the contour of the crossed barberpole configuration (Gorssberg & Mingolla, 1985). Finally, the current model has no conception of 3-D space, and so cannot account for the dependence of the barberpole effect on perceived depth, found by Shimojo, Silverman, & Nakayama (1989).

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