
“On the visually perceived direction of motion” by Hans Wallach: 60 years later

Sophie Wuerger

Communication and Neuroscience, University of Keele, Keele, Staffs, ST5 5BG, UK

Robert Shapley

Center for Neural Science, New York University, New York, NY 10003, USA

Nava Rubin¶

Vision Sciences Laboratory, Harvard University, Cambridge, MA 02138, USA

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In 1935, Hans Wallach published his doctoral thesis at the University of Berlin as a paper in the *Psychologische Forschung* titled “On the visually perceived direction of motion”. His paper is about the perception of the direction of motion and how it is influenced by perceptual organization. Wallach’s pioneering work is not only of historical interest, but also of contemporary scientific interest. It addresses many important issues related to the interaction between motion perception and form perception. A small part of the 1935 paper was translated from German into English by Wallach himself in his book *On Perception* (1976). However, we felt that it was important for the English-speaking vision community to have access to this remarkable scientific work in its entirety. Therefore we offer here its first complete translation into English.

Wallach’s 1935 paper begins with an exposition of the inherent ambiguity of the direction of motion of a line (figure 2)—which years later became known as ‘the aperture problem’. Mathematically, a line with no identifiable features on it does not possess a well-defined direction of motion. However, perceptually such a line is always seen to move in the direction perpendicular to its orientation. Wallach found that, when the line moves behind an aperture, the perceived direction of motion changes from the perpendicular direction and is affected by the shape of the aperture. Therefore he used the perceived direction of motion of lines in apertures as a tool to study how motion signals from two-dimensional (2-D) features are integrated across space and time to yield a motion percept.

After pointing out the inherent ambiguity of the motion of a featureless line and the removal of the ambiguity by 2-D features, Wallach turns (Section II, Part 2) to introduce and develop the notion of ‘identity’. He observes that, although the moving line is physically featureless, the points comprising it are perceptually individuated (‘identical’), and each of the possible perceived motions of the line is associated with a specific path traversed by such points that have a perceptual identity.

Many of Wallach’s observations are relevant to contemporary research, and have implications not only for the study of motion perception but also form and color perception. His results provide evidence against a modular scheme of visual processing, where form, color, and motion are computed in isolation. Instead, he found that the perceived direction of motion was linked to the perceptual organization of the scene: when several interpretations of the form exist, and several directions of motion are possible, only certain combinations of form and motion are perceived. Furthermore, Wallach stresses the point that the linkage is not simply causal (such that, for example, perceived form determines direction of motion, or vice versa), but rather

¶ Present address: Center for Neural Science, New York University, New York, NY 10003, USA.

that each perceptual aspect can influence others, and that therefore form, motion, and color should be viewed as ‘coupled’. This coupling is well demonstrated in a multitude of experiments. In the course of reporting the perceived direction of motion for various stimuli, Wallach describes the perceptual phenomena which are nowadays known as amodal completion (Section II §7; Section III §1; Section IV §13), illusory contours (Section IV §12, §13, §18), neon color spreading (Section IV §14), and coherence versus transparency in plaid patterns (Section IV §15–§17). In each of these cases, he points out the coupling between the figural interpretation and the perceived direction of motion.

In Section IV §19, Wallach lays out a theoretical framework in which to understand his observations. He points out that there is not, in general, a one-to-one correspondence between a stimulus and a percept. Instead, the correspondence should be sought within the perceptual domain. He makes a distinction between different kinds of perceptions of line endings; this is the distinction that is now known as ‘intrinsic’ versus ‘extrinsic’ terminators (Shimojo, Silverman, and Nakayama, 1989 *Vision Research* 29 619–626). Wallach explains that there is a correspondence between the type of perceived line ending and scene organization. He further observes that endpoints can be seen as extrinsic even in cases where the physical stimulus does not contain direct cues for occlusion; in such cases an illusory occluding surface is always perceived. The converse is also possible: it is often the case that observers are aware of the fact that the line termination is due to there being an occluding aperture, and yet the line motion follows the path of the terminator. In these examples and others, Wallach’s findings reveal the inner workings of perception.

Reading this paper is an intellectual challenge as well as a very enjoyable experience; we hope that it will stimulate even more thought than it did 60 years ago.

Note to the reader: We added comments in the text where we thought they were needed; these are set off by brackets [...]. Wallach used italics for emphasis, and they are preserved in the translation. We emphasized some other places with underlining. Also, we wrote figure legends and a table of contents.

Note added in proof: We have produced a computer demonstration that simulates many of the stimuli Wallach describes in his 1935 paper. The program runs on any Macintosh computer. To obtain a copy of the program, use an ftp client (such as “Fetch”) to connect to **cegeste.cns.nyu.edu** using “anonymous” as the user name. Go to the folder “Pub” and get the file “Wallach_demo.sea”. Once transfer is complete, double-click on the file and it will generate a “Wallach Demo” folder. Follow the instructions in the “ReadMe” file inside the folder to view the motion demonstrations.

The following address—**wallach.demo@cns.nyu.edu**—is where to report problems with obtaining or operating the program.

On the visually perceived direction of motion[†]

by Hans Wallach

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[†] “Über visuell wahrgenommene Bewegungsrichtung” *Psychologische Forschung* **20** 325–380 (1935)

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Introduction: The motion of a straight line

One describes the direction of a given motion by specifying the path covered. Usually the direction of *perceived* motion can also be thought of as determined by the physical path that a point or an object travels. However, such a description is not readily applicable to the case we consider in the following pages.

There are visual objects for which there is no correspondence between change in position and a geometrically unique direction. Infinite straight lines are such objects. But this indeterminacy of direction cannot be sensed in the percept of motion obtained from such a stimulus. The phenomenal experience of motion that is elicited in us by the displacement of a straight line has a very specific directionality which does not differ from that seen for other objects whose direction of motion is determined objectively by the path they travel. We will attach the greatest importance to these facts, since we see in them the prerequisite for understanding the phenomena reported here.

To begin with we report a simple experiment: the observer looks from a short distance at a large white screen, whose only visible inhomogeneity consists of a straight, smooth line extending diagonally over the entire screen from the upper right to the lower left corner (figure 1). The dimensions are chosen such that the borders of the screen lie so peripherally in the visual field of the observer that they cannot be perceived. Consequently, a small motion of the screen in its plane will be visible to the observer only as a displacement of the line. For example, if the screen is displaced horizontally by a small amount towards the right, then the observer does *not* perceive the line moving in this direction; rather he perceives a motion diagonally towards the bottom right, that is perpendicular to the orientation of the line; furthermore, the direction of its motion remains the same when the screen is moved vertically downwards by a small amount. How is that possible?

We insert a brief kinematical observation. Suppose a line is displaced parallel to its own orientation in the plane of the figure (figure 2). Let G_A be a part of the line at

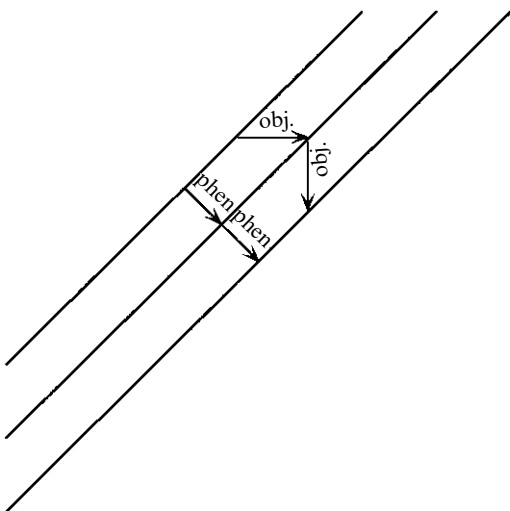


Figure 1. A line with no identifiable feature which is long enough so that its endpoints fall in the peripheral field is always seen to move in a direction perpendicular to its orientation, regardless of the objective direction of motion (in the physical apparatus).

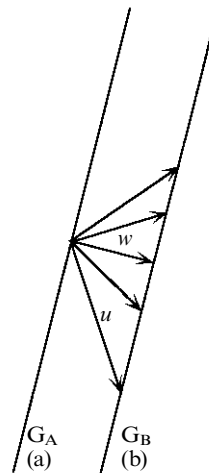


Figure 2. The direction of motion of an infinite smooth line is (mathematically) indeterminate: for example, if the (objective) velocity of the line is given by the vector u , all the other vectors drawn are also possible velocities of the line. The only objective discrimination that can be made is in which half-plane direction the line is moving (eg here rightward and downward, as opposed to left and up). [Wallach defines this property as the sense of motion.]

a specific time (a), at which it has the position A; let G_B be the part of the line at a later time (b), at which it passes through the location B. By specifying the locations A and B, the displacement of the line in the time interval ab is fully determined if we add that b happens later than a, and that rigid motion is assumed. That is, if we are dealing with a mathematical line without limits, then it is meaningless to specify a particular direction in the plane of the displacement, if no specific point-by-point matching is undertaken. None of the directions indicated by arrows would be impossible, none is distinguished as the correct one.

For further discussion, it is useful to introduce an unconventional conceptual distinction. *Perceptually* the line—although it does not have a physically specified direction—is seen to move only in one specific direction, so that each point on the line travels a specific path. By convention, we will call the tangent of this path the *direction* of motion, but in such a fashion that this concept—contrary to the colloquial usage—does not contain the description of how this path is traversed, for example from left to right or vice versa. And through a specification of *this* we shall define what we call the *sense* of motion. In this terminology a displaced line has objectively, and kinematically, a sense of motion, but no direction of motion.

A (mathematical) straight line is a mathematical thought-construct; however, perceived objects are bodies of the real world. An object that is moved rigidly has a definite direction, which can be determined by following the path of a particular point of the object, for example any particle of the screen in the above-mentioned experiment. However, if the moving object is presented to the observer exclusively visually—as in our experiments—and if, furthermore, only straight parallel borders and homogeneous areas of the presented object are visible, then the identification of a particular point and the determination of its path are rendered impossible. In other words, the physical direction of motion is no longer represented in the proximal stimulus. With the lack of identifiable points, any arbitrary direction lying in the sense of motion will become equally probable. Then the occurrence of displacement is no longer capable of determining the direction of motion. If they lack physically identifiable features, (physical) straight lines, contours, and edges have no more a direction of motion than a mathematical straight line does.

In the following we will refer to homogeneous physical lines without visible limits as ‘straight lines’, and this expression shall specifically draw attention to the objective-kinematic property described above. What was said about the (mathematical) straight line holds also for the (physical) straight line—it does not have a unique direction of motion.

However, if one observes the displacement of a straight line, no lack of direction of motion is sensed: a motion with unique direction is perceived. But since the event of displacement does not specify the direction of motion uniquely, the same displacement event can elicit a variety of different motion percepts under other different conditions. A correspondence between the perceived direction of motion and the direction of motion given by the apparatus sometimes occurs, but only by chance. All the directions lying in the sense of motion are possible; that allows for a range of almost 180 degrees.

The direction of motion *that is seen* is determined *figurally*. If the straight line is infinite for the observer because the ends fall in the periphery of the visual field and cannot be perceived, then the line is perceived to move, as we saw before, orthogonal to its own orientation; if the line is displaced within an aperture, then the perceived direction of motion depends on the shape of the aperture, as will be revealed in our investigation.

Pleikart Stumpf¹ observed the (perceived) perpendicular direction of motion of a straight contour which was moved effectively diagonally to its orientation, and recognized that perception

¹ Pleikart Stumpf, 1911 *Z. Psychol.* I 321.

of the objective direction depended on the availability of 'identifying points'. "Small irregularities in the drawing of the figures easily caused an abrupt change to the true direction of motion." He also observed an irregular succession of directions "in the manner of a rivalry" between the true and the perpendicular direction of motion. Reading his explanations, however, does not convey the impression that he attaches the same meaning to these facts as we do. His intention, to formulate laws of motion related to retinal processes, is far from our approach. The observed direction of motion perpendicular to the orientation of the line is insightfully explained by Stumpf as the resultant of all *possible* directions, which are indeed grouped symmetrically around the perpendicular.

The perceived direction of motion of straight lines is, however, not only an indicator of figural effects (namely the effects of the form of an aperture) but deserves special consideration in a wider context. Once more we return to the lack of relationship between the physical and the perceived direction of motion of a straight line and establish the following: the direction of perceived motion is not determined purely kinematically. The perceptual occurrence thus differs significantly from the one given by the stimulus—similar to the case of stroboscopic motion, where continuous perceived motion corresponds to separated, successively occurring single stimuli. It is hardly necessary to point out that stroboscopic motion constitutes such an important subject of research just because of this characteristic deviation of the perceptual from the real.

The figure–ground problem belongs here as well, and the analogy is especially close in this case. The property of being-a-figure is a perceived property; the only real things that are given are the spatial and chromatic relations. Nevertheless, it is not left to chance which parts of the field perceptually obtain the character of figure and which ones the character of ground. Rather, there exists a dependence on all the stimulus relations that are given. But not every constellation causes a *unique* figure–ground interpretation. It is especially these ambiguous configurations that have provoked the investigation of the figure–ground problem.

Our subject of investigation is analogous: the direction of motion of a straight line exists only in the perceptual domain; it is not given in the stimulus. We already mentioned that the perceived direction of motion depends on the shape of the aperture. Finally, we shall also report on stimulus constellations that lead to more than one possible perceived direction. These cases occupy an especially large part of our experiments.

Our investigation is concerned with the effect of the shape of the aperture on the perceived direction of motion.² But before continuing, we have to dwell on a fundamental point. We established that there is no direction of motion given in the stimulus constellation of the motion of an infinite line. Always, however, a specific direction is perceived. Furthermore, this is also the case when the figural relations do not imply only one direction: as mentioned above, in certain cases our stimuli allow more than one possible interpretation. In those cases, the indeterminacy expresses itself as a change in the perceived direction under extended observation. But at any given moment only one specific direction is perceived. It seems as if the percept of motion must necessarily have one direction. The existence of a well-defined direction is obviously a specific property of perceptual motion processes.

Section I. The motion of a straight line in an infinite field

§1. *Methods*

The straight lines were drawn on paper ribbons that were attached at the ends to form closed tapes. These ran over two cylinders, one of which could be rotated by a motor. We employed two different arrangements. In the first one (i), the second cylinder was hanging in the paper tape. Through its weight it held the paper tape tight vertically

² The experiments were performed during 1927 and 1928. Let me warmly thank Professor Köhler for his support and for much advice.

and pulled it firmly across the upper, driving cylinder. Sprockets near the cylinder ends engaged the perforation of the paper tape and provided good motion transmission. The cylinders were arranged vertically above each other, and the flat part of the tape between them was used for stimulus presentation. A screen was placed in front of the tape with an aperture that allowed a part of the tape of the desired shape to be visible. [The screen was white, of approximately the same reflectance as the tape, so that the contrast between screen and aperture was low (H Wallach, personal communication)]. When the paper tape was put in motion, the line drawn on it moved through the aperture.

The subject was sitting at a distance of approximately 1.5 meters from the screen and observed the passage of the line, which occurred every time the paper tape completed a full revolution.

The first arrangement has the disadvantage that only vertical motion of the paper tape is possible. Therefore we made up a second one (ii). The paper tape was moved across a horizontally placed board, which carried two cylinders on opposite ends. One of them had sprockets attached to it and provided the driving force. The required tension was provided through a third cylinder, which hung free in the part of the tape running underneath the board. Parallel to the edges of the tape, thin ledges were mounted on the board on which the screen, with aperture, rested—so that the tape could move freely behind the screen. This arrangement was, together with the motor, affixed to a tripod. It could be revolved around its vertical axis such that the board rotated around its midpoint in the horizontal plane. In this way, motion of the tape in all directions in the plane was possible. Above the middle of the board, the image of the aperture was projected onto a wall through an opaque overhead projector. Thus, the image of the aperture was again in the frontoparallel plane of the observer.

These arrangements only allow translational, not rotational, motion of the object. Our investigation is restricted to this form of motion. Furthermore, only motion in the frontoparallel plane was employed, and all cases involving the depth dimension were excluded.

§2. *The experiments*

With arrangement ii we first tested the observation of Pleikart Stumpf. We let a straight line that was not occluded by the screen pass through the field and moved the subject as close as possible to the projection wall, such that the edges of the images were visible only peripherally. Under these circumstances we confirmed Stumpf's observations completely. In all experimental variations the straight line was seen to move perpendicular to its orientation. Thus, the perceptual direction was only dependent on the sense of motion and orientation of the line.

For this experiment, we made a variety of paper tapes, for which the orientation of the line on the tape varied, as shown in figure 3. Panel 3, for tape 3, depicts the size of the aperture reflected by the overhead projector. When these tapes were presented in succession, even though all of them had the same objective direction of motion, eg vertically from the top towards the bottom, for each of the tapes a different direction of motion was perceived (see the small arrows in the drawing), because the orientation of the line was different in each case. However, if we rotated the apparatus from trial to trial, so that the orientation of the line was kept constant [using different tapes], while the objective direction was changing, then the perceived direction of motion remained the same and the subject did not recognize that objectively different directions of motion were presented.

Many people might be inclined to talk about this as an 'illusion'. After all, another direction of motion, different from the objective one, is perceived. However, from our explanation in the Introduction, it follows that the appearance of a direction different from that objectively presented should not be called an 'illusion'. Rather, the perceptual

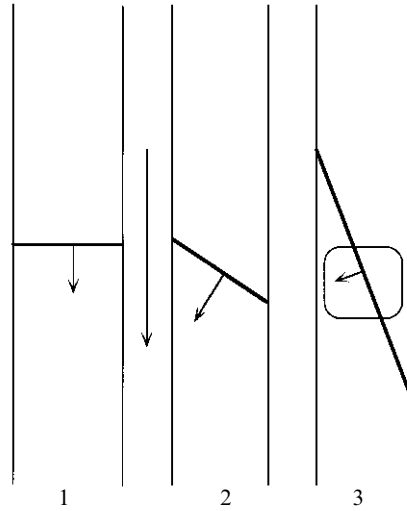


Figure 3. The experimental setup (arrangement ii). The objective direction of motion of the paper tape is indicated by the long arrow (vertically downwards here). The orientation of the line was varied (panels 1–3). The line was seen through an aperture as shown in panel 3. The perceived direction of the line in each case is indicated by the small arrows. The whole apparatus could be rotated in the frontoparallel plane, so that objective motion was not limited to the vertical axis.

and the retinal course differ already in that a particular direction of motion is seen *at all*, since the proximal stimulus possesses no direction of motion. For example, the objective and the perceived motion could agree by coincidence. For panel 1 (figure 3) this is in fact the case. Nevertheless, the relation between the physically objective and the perceived direction is the same as for the other panels: kinematically, there is no feature here that could determine the direction of motion.

A prerequisite for the reported experimental results is, of course, that the lines are drawn uniformly enough and that they do not provide any identifiable points. In the experiment without an aperture, the true, objective direction of motion of the line is perceived easily if the slight texture of the paper becomes visible and thus the direction of motion of the tape becomes noticeable.

Since the subject had to sit close to the projection wall in this experiment so that the images of the edges of the projection were sufficiently peripheral and not to make the stimulus look like an aperture, we projected the tape onto the bare wall of the experimental room. This was a plaster wall painted with oil paint, whose even texture was so strong that the projected micro-texture of the paper tape was invisible.

The cases in which the objective direction of motion is given by some feature with, or on, the straight line will be considered later (in Section III).

§3. *The distinction of the direction of motion perpendicular to the orientation of the line*

According to Pleikart Stumpf the perceived direction of motion, namely that perpendicular to the line orientation, occurs because it is the resultant of all possible directions. For each oblique direction (eg a in figure 4), there exists a direction (a') that is placed symmetrically around the normal (s). If these two directions are seen as the resultant of their respective normal and tangential components, the two tangential ones cancel each other, since they are of opposite direction and of the same magnitude; the normal components remain. This holds for all oblique directions, for they can be ordered pairwise like a and a' .

A different interpretation is as follows: suppose the straight line G (figure 2) is displaced from A to B . u and w are two possible directions lying in the sense of motion. They constitute, so to speak, two equally valid manifestations of the displacement. It is easily seen that the line travels a shorter distance to go from A to B if it is following

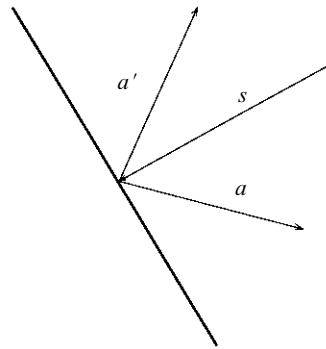


Figure 4. Pleikart Stumpf's explanation why the perceived direction of motion is perpendicular to the line orientation: it is the resultant [vector average] of all possible perceived directions.

the direction w , and that the perpendicular direction always constitutes the shortest of all possible paths. If the line is not moving perpendicular to its own orientation but, for example, in direction u , a higher speed would be required to travel the longer distance in the same time period. For a constant speed of the tape, each angle of all possible directions of motions is, for geometrical reasons, associated with a different speed. In the orthogonal direction, the line has to travel the shortest distance, and therefore with the slowest speed. This suggests that one might attempt an interpretation of the distinction of the direction perpendicular to the line orientation in terms of energy minimization.

We are, however, content with the statement that the direction of motion observed in Stumpf's experiment is figurally special. The right angle is generally special for space perception, and the question which particular mechanism has to be considered as responsible for the 'motion of lines' is sensible to ask only when one moves to concrete physiological theories.

Recently Oppenheimer has published experiments with induced motion³ that are closely related to our question. In that work, too, the perceived direction of motion was investigated for cases in which in the stimulus constellation produced a displacement of undetermined direction. Short straight luminous lines were moved towards each other in the dark so slowly that the motion remained subjectively subthreshold. Objectively, one line moved towards the other one, which was stationary; what was perceived was that *both* lines moved towards each other. But not only the magnitude of the motion, through which the two lines accomplish the displacement indicated by the stimulus, is 'free': so is the perceived direction. It is by no means determined by the shortest distance. The lines were always perceived to move in a specific straight direction. The motion in the direction of their orientation was preferred; besides that, only the direction perpendicular to their orientation was perceived.

Section II. The motion of a straight line in apertures of different shapes

How does a straight line travel through an aperture? To answer this question we conducted a large number of experiments, of which a selection will be reported here, to characterize briefly the processes which occur and to identify the effective factors.

Part 1. The perceived direction of motion

The experiments reported in this section could all be conducted with arrangement i, which only allowed objectively vertical motion, since variation of the objective motion was unnecessary. The perceived direction of motion depends—apart from the shape of the aperture and the orientation of the line—only on its sense of motion. The objective direction of motion plays a role only in determining the sense of motion [ie left vs right, or up vs down]. Figure 5 demonstrates once more the relationship between direction and sense of motion. The solid arrow indicates the objective direction of motion, the dotted ones denote the possible directions lying in the sense of motion. In the description of the

³ Oppenheimer *Psychol. Forsch.* **20** 1–46.

experimental conditions, we only have to specify the sense of motion of the line. In the following we shall, however, for the sake of simplicity, indicate the sense of motion by *one* arrow in the schematic drawings of the experiments. From the previous explanations it is clear that any direction lying in the (possible) sense of motion would indicate the sense of motion. Therefore, it is not necessary that the arrow coincide with the objective direction of motion; the latter is irrelevant.

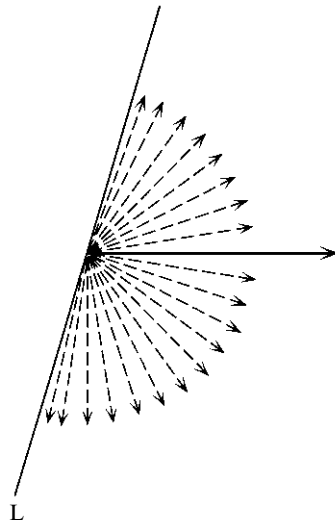


Figure 5. The relationship between the direction of motion and the sense of motion. While the objective direction of motion is not measurable for a line with no identifiable features (figure 2), the sense of motion is uniquely determined, and is given by the collection of direction vectors which lie on the same half-plane (relative to the line orientation) as the objective motion direction. The sense of motion limits which motion directions can be perceived.

§1. *The direction of motion in the square and the rectangle*

A straight line moves diagonally through an aperture in the shape of a square. It simultaneously passes both of the corners of the aperture lying on its path, and thus forms a diagonal of the square at that moment. Once again we would like to emphasize that in all our experiments the line is translating, ie it remains parallel to itself as it moves. The apparatus allows only translational motion of the object. Figure 6 shows the line at an arbitrary point on its path. Obviously, for the subject the line is only visible within the square which constitutes the aperture in the screen.

The arrow drawn inside the square denotes the perceived direction of the motion of the line. In this case it travels through the aperture diagonally, that is perpendicular to its own orientation. If one changes the line orientation with respect to the aperture by placing it at a steeper angle, then the subject notices, especially for slow displacement,

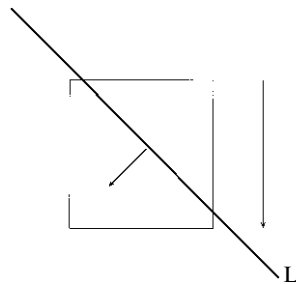


Figure 6. The perceived direction of motion of a 45° oblique line through a square aperture is perpendicular to the line orientation throughout the motion duration. (Objective motion is vertically downwards.)

inhomogeneity in the motion in the middle of the run, and good observers report that the line is moving horizontally for a very short stretch. If the square is elongated in the horizontal direction to produce a rectangle (figure 7), then the horizontal stretch of motion becomes obvious for most subjects. The passage of the line then follows a beautifully sweeping curve similar to the one illustrated in figure 7. To determine the origin of this effect, we greatly reduced the speed of the line and obtained, instead of a smooth curve, motion with two sharp bends. From its entrance into the aperture at the top right, the line is perceived to move obliquely downwards towards the left until it passes corner A, then it is seen to move horizontally to corner B, and then is perceived to travel again obliquely in a similar direction as in the first part of its path before the sharp bend. Now, in the first part of its path the line intersects the aperture edges a and b, which form a right angle with each other, then a and c, which are parallel to each other, and finally c and d, which are again perpendicular to each other. *The perceived direction of motion of a sufficiently slowly moving straight line thus depends on which pair of aperture edges it intersects.* If the line runs between [and therefore terminates at] the parallel edges a and c (figure 7), then the perceived direction of motion is parallel to them; if the line intersects nonparallel edges, then it is perceived to move in a direction intermediate between the orientations of the edges. For sufficiently slow speed, this rule held good for apertures of diverse form.

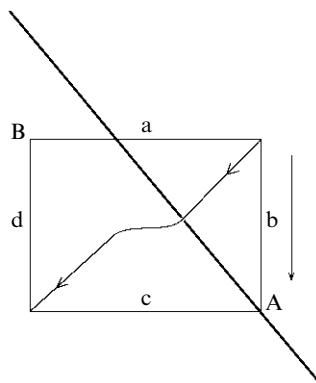


Figure 7. A 45° oblique line is perceived to travel in a curved path as it passes through a rectangular aperture (for details see text).

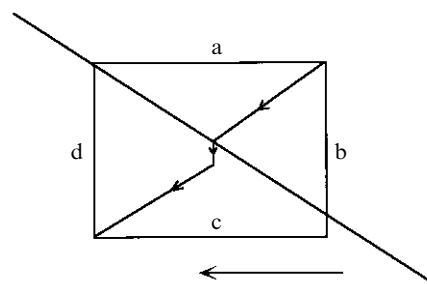


Figure 8. The perceived path of a line through the same aperture as in figure 7 when the orientation of the line is shallower than the diagonal of the aperture.

When one goes on from these low speeds to higher ones, then the sharp [perceived] bends become rounded off and curves are observed as in figure 7. With increasing speed the perceived curvature diminishes, and for even higher speeds the paths of the line become straight. Then they do not run any longer from corner to corner but lie more horizontally; the lines then are perceived to move through the aperture in a uniform direction which is intermediate between diagonal and horizontal. We think of this curve as being generated more or less through mutual assimilation of the single stretches [segments] of perceived direction, which are determined by the pairs of edges intersected by the lines. Depending on the proportion of the perceived horizontal stretch, the flattened curve will run more horizontally or more obliquely.

The proportion of perceived motion in the horizontal direction changes with the orientation of the line with respect to the aperture. If the line intersects the rectangle at a steeper angle, then the path of perceived horizontal motion when the line runs between the parallel edges is expanded at the expense of the stretches of oblique motion. The extent of perceived horizontal motion becomes shorter and shorter the shallower the line orientation, and is entirely eliminated as soon as the line orientation equals that of the diagonal of the aperture. At this orientation, the line passes the points A and B simultaneously, and the parallel edges a and c are never

intersected at the same time. Accordingly, the line is perceived to move for all speeds in a uniform oblique direction through the aperture. If the line orientation is even shallower, so that b and d are intersected simultaneously during the line motion, then that part of the path where the line intersects the parallel edges b and d looks vertical; figure 8 shows the curve that describes this motion. Finally, in extreme cases, if the line is oriented either vertically or horizontally, then it intersects only two edges throughout its motion and therefore is perceived to travel uniformly along a path parallel to them.

§2. *The ‘parallelogram in a special orientation’*

A special, and in the further course of our experiments particularly important, constellation is one where the aperture shape is as drawn in figure 9; it has the form of a parallelogram of which one pair of edges is parallel to the [moving] line. A straight line indeed appears to move in a uniform straight direction, parallel to the edges, through such a ‘parallelogram in a special orientation’.

§3. *The direction of motion in the triangle and in the L-shaped aperture*

There are aperture forms that cause a change in perceived direction that is preserved even for relatively high speeds. This is the case if the change in direction is more pronounced than in the rectangle. For example, through a triangular aperture, a line like the one depicted in figure 10 is first seen to move vertically until the lower right corner is reached, and then, once the base is intersected, it is seen to move at a shallow angle or even horizontally leftwards. The bend in the perceived direction of motion is sometimes very sharp; the change in direction can be as much as 90 degrees. The descriptions subjects give of the perceived direction of motion in each stretch are not consistent. Most of the times they see the line move vertically in the first stretch. However, oblique directions, a bit towards the right or left, are sometimes reported. If the line was perceived to move slightly obliquely rightwards in the first stretch, then the change to the new direction is sharp and acute; in the other case the motion is more along a smooth curve.

The results are different for the L-shaped aperture of figure 11. Here a change in perceived direction by exactly 90 degrees always takes place whenever the line passes the corners E and F. Before and after that, the perceived direction of motion is vertical and horizontal, respectively. (Here we disregard the oblique portions of the motion [through the right angled corners] at the beginning and at the end of the path.) If one chooses a line orientation like that depicted in figure 11, then the change in perceived

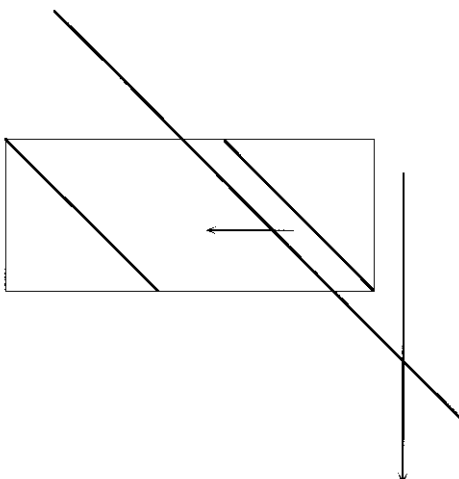


Figure 9. Motion through a ‘parallelogram in a special orientation’: the two oblique sides of the aperture are parallel to the line orientation, so that it appears fully in the aperture all at once. The perceived direction of motion is horizontal throughout the line passage.

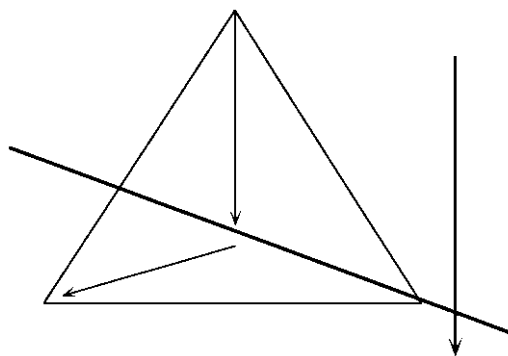


Figure 10. Motion through a triangle-shaped aperture. The change in the perceived direction is dramatic and occurs even for high speeds.

direction is abrupt for all speeds. This result is altered at once if [the orientation of the line is changed so that] the line does not pass the corners E and F simultaneously (see figure 12). In such a case, when the line has reached F, it still has to face the thickly drawn part of a, and therefore it travels through that piece while it already intersects the horizontal edge b with its other end. For a very short piece, the line is therefore moving in between edges that are tilted with respect to each other and this corresponds to the oblique part of the trajectory (drawn in figure 12) that is perceived for most slow motions. If one goes on to higher speeds, then the change in perceived direction traces a smooth curve.

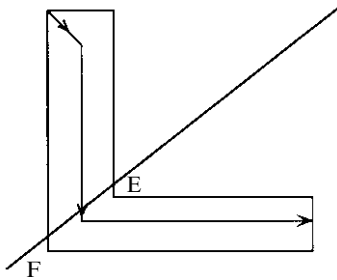


Figure 11. Motion of a 45° oblique line through an L-shaped aperture. The line is seen to move vertically downwards until it reaches points E and F; at this point its direction changes abruptly to horizontal.

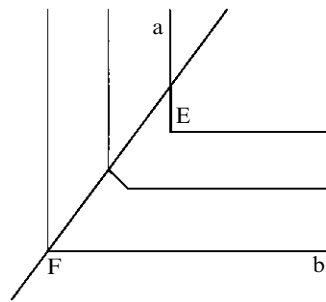


Figure 12. If the line passing through the L-shaped aperture is not at 45° orientation, then its passage through points E and F is not simultaneous. In the short interval after passing F and before passing E, it is perceived to move obliquely. For high speeds, the line is seen to trace a smooth curve.

§4. *The tendency towards the direction parallel to the edges*

From the experiments in the triangular and in the L-shaped apertures it follows clearly that the perceived motion of the line between parallel edges is very different from that between angled aperture edges. Between parallel edges, the line is invariably perceived to travel in a direction parallel to them, while the perceived direction of motion in a stretch between angled aperture edges can vary widely from one observation to another. Different perceptions of the directions of motions in successive presentations to the same observer only occur for angled edges; also individual differences of the subjects can only be established for angled edges. (This is not to say that the subjective impression of direction is less definite when the line moves through an aperture with angled edges than when it is passing through one with parallel edges. In all cases a specific direction of motion is perceived. The different behavior of the perceived direction of motion in the angle is merely established through comparison of the results across different trials.)

When looking for an explanation for these results we have to take into account the following. However different the perceived direction of motion may be in one and the same angular portion of its course from one trial to another, the direction of the line always lies within the area bounded by the orientation of the two intersected edges; this was found in all experiments. Note that this rule accounts both for the observed direction of motion between angled *and* between parallel edges: as the angle between the aperture edges becomes more acute, the play in the differences in direction becomes smaller and smaller. Finally, when the sides become parallel, the play goes to zero, and hence only one perceived direction is possible.

The above rule, however, is not sufficient to predict completely the perceived direction of motion in angled apertures. If it were only a matter of the perceived direction not

lying outside the area bounded by the edge orientations, then, within these limits, the perceived direction of motion might be independent of the shape of the aperture. This is not the case as we will show. [Wallach only returns to this point in Part 2 §9 (figures 17 and 18).]

Next, we tested the perceived direction of motion for *one* edge. In this case, the line travels partly behind a screen with a straight border and ends on the opposite side in the peripheral visual field. Under these conditions (figure 13), the line is perceived to move parallel to the border of the screen for all orientations of the line as long as the observer is not too far from the screen [so that the other end of the moving line falls far enough in the periphery to have no influence on the perceived direction].

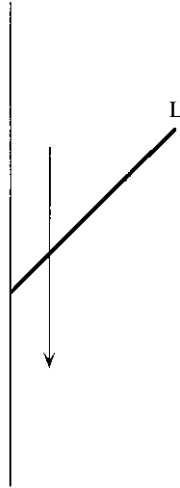


Figure 13. The direction of motion for one edge. The opposite end of the line is in the periphery. The perceived direction of motion is always parallel to the edge.

The following hypothesis about the dependence of the direction of motion on the shape of the aperture seems to fit the facts: the straight line has a tendency to appear to move parallel to the aperture edges that it is intersecting at that point in time, as if the point of intersection with the edge were an objective feature for the direction of motion. If both intersected edges have the same orientation, then the tendencies for both edges agree; if they are angled such that the direction tendencies diverge, then an intermediate direction results. [In Part 2 §9, figures 17 and 18, Wallach describes experimental results which determine what this 'intermediate direction' is.]

§5. *The effect of fixation of the edge*

In the experiments about motion in an aperture, which were conducted with arrangement i, the size of the aperture was up to 9 cm in length. The distance between the head of the subject and the apparatus was approximately 1.5 m. The visual angle of a length of 9 cm was therefore approximately 3 deg 30 min. In arrangement ii all measures were magnified by a factor of $4\frac{2}{3}$ through projection. The distance of the subject from the projection area was 7 m, and was therefore magnified in the same proportion as the presented object, such that the visual angle remained constant. Nevertheless, it was noticeably more difficult to get an overall picture of the aperture when presented with arrangement ii because of the larger perceived size. This is the disadvantage of arrangement ii.

If the subject is near enough to the plane of the screen so that not all aperture edges are clearly seen simultaneously, then the perceived motion depends crucially on the direction of gaze. Consider the case where the line passes through a square aperture (figure 6). When one looks at the upper edge, the line appears at first to move horizontally until the top left corner is reached and then it is perceived to move vertically; in contrast, when the gaze is directed towards the right edge, the line is first seen to move vertically towards the right bottom corner and then horizontally.

It thus moves parallel to the edge selected by the direction of gaze; this is independent of whether one fixates a point on the border or whether one tracks the line ending with the eye. This influence of the direction of gaze is very important and can be proven even for apertures of small sizes like those employed in our usual experiments [arrangement i, 1.5 m]. Certainly the direction of gaze plays a role if, for repeated presentations of the same stimulus configuration, different directions of motion are perceived in the angular part of the path. It should be noted that, when the line moves between parallel edges, the direction of gaze towards one or the other of the edges is of no consequence because the two edges have the same orientation.

§6. *The absolute tendencies of direction*

The tendency to follow the direction of the intersected edge constitutes by far the most important factor in determining the perceived direction of motion. For angled apertures, we found two additional factors that were effective. These are the tendency to perceive motion perpendicular to the line orientation and the preference for the principal directions of space: perceptual horizontal and vertical.

The experiments reported below were conducted with arrangement ii. A cardboard with an aperture in the shape of an angle of 60 degrees served as a screen together with a second piece of cardboard with a straight border, which functioned as an adjustable base to the sides of the triangle. The latter was always adjusted to be parallel to the [moving] line so that it only intersected the other two edges as it passed through the resulting triangular aperture. This setup, therefore, caused the line to follow a trajectory with a uniform direction. In this way, the direction of motion in the angle, or corner, could be investigated in isolation. To prove that the tendency towards seeing motion perpendicular to the line orientation also takes effect in an aperture, the vertex and the sides of the triangle always remained in the same position, and merely the orientation of the line was varied between presentations and the base was adjusted correspondingly. (Thus the length of the sides was, of course, altered.) Figures 14 and 15 show two such variations. In figure 14 the line and the base intersect the sides symmetrically, therefore yielding an isosceles triangle. In this case the perceived direction lies exactly midway between the intersected edges [along the angle bisector]. However, this also coincides with the direction perpendicular to the moving line itself. [Therefore, this isosceles setup cannot distinguish between the two possibilities.] If one now varies the orientation of the line [from trial to trial] with respect to the fixed screen, the perceived direction of motion first runs in the direction of the height of the triangle, ie the direction perpendicular to the line orientation. Only after more pronounced rotation of the line, as in figure 15, does it deviate from perpendicular motion and is seen to travel in the direction of the bisector.

If one rotates the entire constellation of figure 15 a little bit between presentations, such that its orientation varies, then usually there are wide zones in which the motion is perceived as horizontal or vertical. That happens especially in those cases in which the height of the triangle, or the angle bisector, and in particular the range of directions between them, lies near horizontal or vertical. This preference for the principal directions of space differs between individuals.

Despite the preference for vertical and horizontal, and despite the tendency to see the line move in a direction perpendicular to its orientation—we put both of them together with the label ‘absolute direction tendencies’—our experiments demonstrate clearly that a particular intermediate direction, resulting from averaging the directions of motion of the two intersected edges [which is equivalent to the direction of the bisector], may prevail over both ‘absolute direction tendencies’.

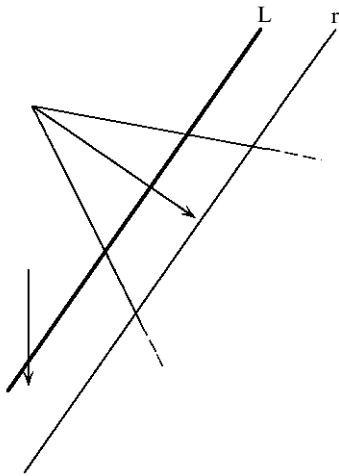


Figure 14. The direction of motion through an angled aperture and the tendency towards motion being perpendicular to the line orientation. When the line is oriented so as to form an isosceles triangle with the aperture edges, the perceived motion is perpendicular to the line orientation. The same result is obtained when the orientation of the line is changed slightly, so that it does not intersect the two edges symmetrically.

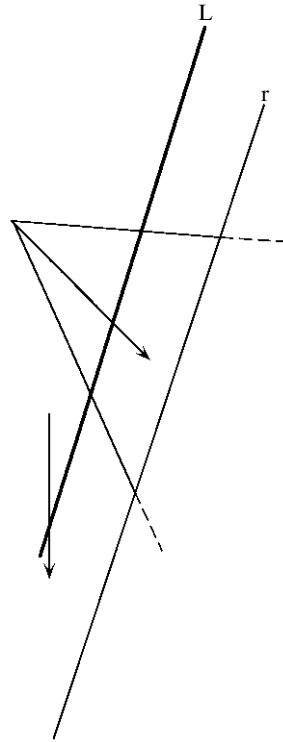


Figure 15. Only after the line orientation is changed more pronouncedly does the perceived direction deviate from that perpendicular to the line orientation.

Part 2. Identity

§7. *The changes of the line when passing through the rectangle*

[Wallach uses the term ‘identity’ in two senses, which are related, but different. He makes two claims:

(a) Although the line is featureless, *perceptually* each point on the line has an ‘identity’, in the sense that the observer keeps track of its trajectory as the line moves. This idea is intimately related to what we nowadays call ‘the correspondence problem’: the crux of Wallach’s insight is that the perception of the direction of motion and the resolution of the correspondence problem are intertwined. Wallach and colleagues later extended this concept to analyze other motion stimuli, such as rotating ellipses (Wallach, Weisz, and Adams, 1956 *American Journal of Psychology* 69 48–59; reproduced in H Wallach *On Perception* (1976, New York: Quadrangle) pp 217–232).

(b) In addition, Wallach uses the term ‘identity’ to describe cases where the moving line is perceived as a physically constant object, even though objectively (in the experimental apparatus) it is comprised of continually changing parts.]

Until now we have described how the direction of motion of the line depends on the shape of the aperture and on the orientation of the line with respect to the aperture. Now we examine *the line itself* during its passage through the aperture, considering first the objective geometric facts. The length of the visible line changes for most aperture shapes. In the rectangular aperture (figure 7) for example, more and more of the line becomes visible as it moves from the entrance point of the aperture towards corner A. While it runs through the intermediate stretch between the parallel edges, its length remains constant but then it again decreases after passing corner B. In brief, the visible length of the line changes continuously while it travels between angled aperture edges, and remains constant between parallel ones.

What is the accompanying phenomenological experience? The line enters at the upper right corner with a small jump into the field of view. Then it is seen to move uniformly in an oblique direction and *grows*. At corner A, or frequently shortly behind it,

the perceived motion becomes horizontal. For some observers this is accompanied by a noticeable jerk, which is probably linked to the increase in speed that is due to the perceptual transition from oblique to horizontal motion. The oblique motion is after all usually closer to the motion direction perpendicular to the line's own orientation, which possesses the lowest speed (see Section I §3). At the end of the stretch between the parallel edges (at corner B), the line again turns gently in the oblique direction. The behavior of the line in the last part of its path is different. Some subjects perceive the line *shrinking*: it becomes smaller until the extinction of the last line segment in the aperture—and finally ceases to exist; for other subjects, it 'leaves' the aperture, *disappears* behind the borders. In this way, the line continues to exist in perception, as odd as this may sound, becoming less and less visible while maintaining its [physical] length. We were not able to establish different directions of motion correlated with these two behaviors of the line.⁴ As opposed to the last segment of the path, the process in the first segment is always the same. Even for those subjects who do not observe a shrinking when the line exits the aperture, the line grows while entering.

[In the paragraph below, Wallach takes a momentary break from his description of the perceived direction of motion, to describe the phenomenological experience related to the line 'disappearance'. This is, in effect, an account of *amodal completion*—one of the earliest available in print. The concept of lines and surfaces completing behind occluders resurfaces later in the paper—see Section IV §2 and §19.]

We were able to communicate splendidly about these perceptual subtleties with observers, all of them untrained subjects without any connection to psychology. As an example for something invisible yet objectively existent, we sometimes showed the subject a ruler that was held behind a corner of the screen such that a segment of its middle was hidden behind the screen. In this case one does not perceive the ends of two separate rulers, but rather a single object that is partly hidden.

The small jump with which the line enters the aperture depends on the speed of the line and also on how strong it stands out from the ground. Fröhlich has described this displacement of the entrance point of a moving object which appears from behind a screen. Characteristically, the direction of this jump is always perpendicular to the orientation of the line, therefore independent of the figural effects of the aperture. This is especially impressive in the 'parallelogram in a special orientation' (see Section II §2). Here right at its entrance the line possesses its entire visible length, which it also has later on while passing through the aperture. In this case the running jump oblique to the aperture edges and to the direction of motion of the line in the aperture is very striking, in particular for higher speeds. For slower motion, the width of the jump is modest, and during the entrance of the line in the corner it becomes only conspicuous during fixation of the point of entrance.

§8. *Identity and direction of motion*

One thing is very clear and probably the prerequisite for the variations [observed in Section II, Part 1]: *the visible line segment retains its identity throughout the motion*. That need not be the case; the stimulus constellation does not require it: objectively no identifying feature is provided. The line is entirely homogeneous [featureless]—this is a prerequisite of the experiments—and objectively one segment can replace another without detectable change (see Introduction). This in fact occurs continuously in the arrangement we used. For example, while the line is perceived to travel in a horizontal direction through the intermediate segment of its course, objectively it moves vertically downwards, and therefore the part of the line visible in the aperture consists of continually changing objective segments of the [physical] line. Figure 16 demonstrates this. It shows the location of an objectively identical line segment (thick line) at two different points in time. Therefore we state: an impression of identity is present in cases where it is not provided by the stimulus. The facts are the same as those described in Section I §2 for the perceived direction of motion: the objective identity relations play no role. The difference between the perceptual course and the objective one is that objectively no identifiable attributes are provided, while perceptually a definite identity exists.

⁴ See Section II §8.

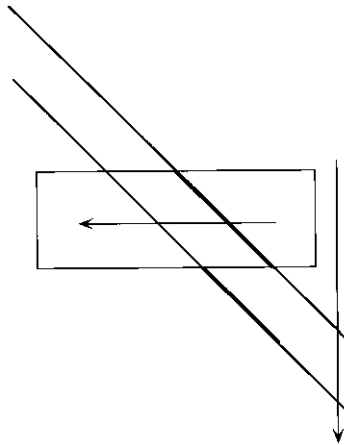


Figure 16. Objective identity and perceived identity. Since the line moves objectively downwards, the part of the line visible through the aperture is continuously changing. However, perceptually the line segment visible through the aperture preserves its identity throughout the motion, as each point on it is seen to move horizontally.

That no identifiable features exist on the straight line is, as stressed previously, a prerequisite for the objective lack of direction of the line. In the Introduction we discussed how identifiable features and the direction of motion are related by simple geometry. The objective direction of motion based on the course of physical points on the line was defined. It would be wrong to presuppose, however, that such a relation takes place in the perceptual domain—namely that the perceived direction of motion is determined by the perceptual identity relations. How perceptual identity and the perceived direction of motion are related is an empirical question, not a subject of assumptions. If, on the basis of our experiments, we reach the conclusion that the perceived direction of motion and perceptual identity are correlated in the same way as physical direction of motion and physical identity are causally related, then nothing a priori self-evident has been said, but in fact an empirical discovery has been made. Here, we claim that both always occur together, and not that one is the first and the other is second. The following rule was confirmed without exception: the perceived direction of motion corresponds to the path traversed by a perceptually identical point on the line. This rule also may be stated the other way round: those parts of the line which retain their identity during the motion move along an imaginary straight line which is parallel to the perceived direction of motion.

The length of the visible line remains constant in its passage between straight parallel edges, as mentioned before. Perceptually, the visible, moving line segment ends at the borders and is a self-contained unit. Only in rare cases it may happen that in these conditions the line is perceived to extend behind the screen: for example, when numerous presentations are given in brief succession. It is conceivable that the line would appear to be emerging continually from behind one edge and correspondingly to be disappearing behind the other one (which is actually what is happening most of the time in our setup). However, we never see a trace of this. Parts (with a perceptual identity) are not perceived to change their position along the visible line. For example, the point that first was perceived to be lying in the middle of the line remains in the middle during the entire passage of the line through the parallel path segment between the intersected edges, and the endings are perceived to travel along the aperture edges without any change. The path each of these perceived parts travels is in accordance with the perceived direction of motion.⁵

⁵ See overleaf

Of a different nature are the perceptual processes in the angular path segment [corner], where the line is seen to grow or shrink. Such perceptual processes are characterized by the situation that different parts of the line are perceived to move radially from each other, namely in such a way that the more peripheral parts travel more than the central ones with respect to a stationary center. The line undergoes these changes as an object of fixed identity. These processes are not as stable for the line in the angular path segment as those reported previously; in fact, they are quite easy to modify—probably because the interior [longitudinal] motion only runs in one dimension, namely along the line towards both edges. A displacement of the stationary part within the line towards an aperture edge is a most asymmetric distribution of the longitudinal motion. It was never observed that the starting point of the longitudinal motion was beyond the aperture edge, or that the line stretched towards one of the edges and shrank towards the other one, even for motion in the angle [corner]. A reason for such a phenomenon could also not be comprehended. The growing and shrinking that is perceived is caused by the physical setup that makes the visible length of the line change continuously. Furthermore, the processes of interior motion occur [perceptually] just as rarely as in cases where no objective cause whatever exists, namely in the path between parallel edges where the visible length of the line remains constant.

If we ask for the relationship between the perceived identity and the direction of motion in the case of motion in the angular path segment, we must consider that a higher degree of identity is associated with that point on the line which is stationary with respect to the longitudinal motion than those parts that are affected by the motion of expansion and shrinking; it is, so to speak, the seed from which the line emerges, starting at its first appearance in the vertex of the angle. The line is represented rather precisely by the stationary center of the interior motion. Through application of the rule of correspondence between perceived direction of motion and perceptual identity, the course of the line should be along the path of this [longitudinally] stationary point. This is indeed true. In the following case this becomes especially clear.

We already pointed out that the processes of growing and shrinking of the line are easily modified [perceptually]. Directing the gaze towards the endpoint of the line (along the aperture edge) has as its consequence that the line ending is no longer affected by the interior motion. Rather, the line now grows or contracts from the ending towards the other edge instead of from the center. The direction of motion should follow the path of this new starting point of the interior motion, and this is exactly what happens. As reported in Section II §5, a direction of motion parallel to the adjacent aperture edge results when the direction of gaze is directed towards the line ending.

⁵ It would also be 'conceivable'—if we transcend for a moment the limits of what appears to us as intuitively possible—that each arbitrary part of the line, independent of its neighbor, might become another arbitrary part of the line; then parts perceived as identical would change their mutual position in the line. The reason that this possibility seems to be excluded from the beginning is obviously because the parts that can be discriminated do not exist in isolation, but *exist perceptually only through the role they play in the line as a whole*. To-be-the-ending, to-be-the-middle, etc—these are functions by which a particular part of the visible line is completely defined. These roles are determined by the aperture edges, since the line appears to end at the edges, as we have seen. Even if the latter would not be the case, the aperture edges are after all the only reality such an allotment of roles could be related to.

In principle, these are the same relations as in the experiments by Ternus (*Psychol. Forsch.* 7 81). There the functions of the parts in the whole determine likewise the perceived identity of these parts. In Ternus's case we are dealing with *isolated* parts of a figure; but they are identical to each other and therefore interchangeable. A figure comprised of points is presented in fast succession at two different spatial locations. It turns out that the function in the figure as a whole determines the order in which the points of one presentation change identically into the points of the other presentation. The stroboscopic motion process *follows* this intuitive identity relation.

§9. *The application of the principle of 'Prägnanz'*

[For a general discussion of Prägnanz ('perceptual goodness') see Koffka *Principles of Gestalt Psychology* (1935, New York: Harcourt Brace).]

When identifiable features are not present, apparently all perceptual characteristics, including the phenomena of interior motion, are subject to self-distribution in the psychophysical system. [We conjecture that the meaning of this sentence is that infinitely many motion interpretations, including nonrigid motions ('interior motion'), might exist perceptually.] On the basis of the previous experience with processes of this kind [ie the accumulated knowledge of Gestalt psychology], we expect to find exactly those identity relations that correspond to relatively *simple* global motion perception.

With respect to the line motion between parallel aperture edges we may argue that the passage of the line as a closed, rigid object, ie the one actually perceived, constitutes a simpler process than any of the numerous other possibilities. The emergence in appearance of the line from behind one of the edges and the disappearance behind the other one, for example, would imply that continually 'new' parts of the lines would become visible in the aperture; but [this is not what happens, rather] the number of perceptually identifiable parts remains constant throughout the entire travel.

Above (Section II §3 and §6) it remained an open question what exactly is the intermediate direction of motion that is perceived when there are different directional tendencies at the two participating edges as in an angular aperture. As demonstrated before, other factors influence the perceived direction of motion in an angle to a great extent, and make the direct inference of a rule impossible. Nevertheless, on the basis of our latest considerations, ie because of the correspondence between motion direction and identity, we can speculate about the direction of motion in the angle, and confirm this by means of specifically designed experiments. If the line, for example, grows during its passage through an angular path segment, then this process should proceed symmetrically. That means that the [longitudinally] stationary center of the interior motion should lie at the midpoint of the visible line segment. Since the starting point of the interior motion, as we saw above, retains its identity with respect to the line, the perceptual direction of motion should correspond to its [the midpoint's] path. The midpoints of the [growing] visible line segment lie on a straight line. Mathematically it is the bisector of the angle between the intersected edges. Thus, the motion is predicted to proceed in the direction of the bisector.

There are several observations confirming this speculation from the experiments on the triangle with a base parallel to the line (see Section II §6). For example, it was reported that during its passage the line grows from the middle uniformly towards both sides, or that the motion direction runs through the middle of the triangle. In these experiments, describing the direction of motion raises great difficulties for many subjects, probably owing to many possible observable relations. One might want to relate the description of the direction either to the aperture or to the projection wall, and since the interior behavior is altered when perceiving the line motion in such a way, different directions of motion can be perceived in the two cases.

Thus we attempted to arrange the experiments so that the subjects were not required to describe the perceived direction of motion. We let a line move diagonally through the aperture in the shape of a parallelogram; thus the aperture consists of two angular path segments, and the line travels smoothly between them. The two corresponding bisectors are indicated by a dotted line in figure 17. Together they form a straight line, the other diagonal in the parallelogram. If our hypothesis is correct, then these constellations should produce a uniform straight direction of motion. Thus the subject is asked the following: Does the line move along a curve, does its path bend, or is it moving along a uniformly straight path? The last is the case.

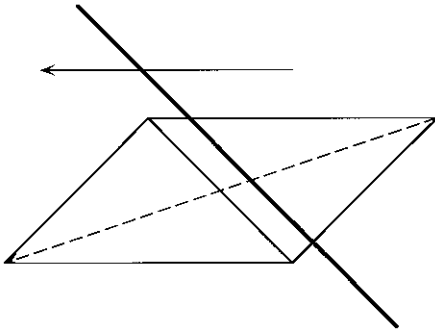


Figure 17. Experiments to demonstrate that when passing through an angled aperture the perceived direction of a line lies along the angle bisector. When a line moves through a parallelogram-shaped aperture so that its orientation is parallel to the (short) diagonal, it is seen to move in a straight path, without bending as it passes the middle of the aperture. Thus, the perceived direction lies along the main diagonal, which coincides with the angle bisector.

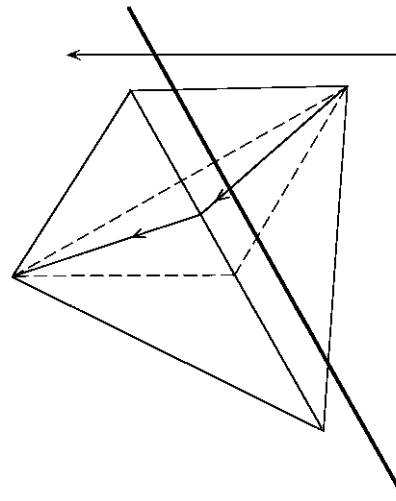


Figure 18. When a line moves through a diagonal-symmetric quadrilateral aperture so that it is parallel to the main diagonal, its path is seen to bend as it passes through the middle of the aperture. This result is inconsistent with a perceived direction perpendicular to the line orientation and is taken to indicate that the line is following the path of the angle bisector, approximately.

[This result is consistent with the explanation in terms of the angle bisector but it is not conclusive because the results of this experiment could also be explained in terms of perceived direction being determined by the tendency to see motion as perpendicular to the line's orientation—that would also give the observed result of a smooth, unbending perceived direction of motion in the parallelogram. The experiment described below was designed to distinguish between the perceived direction following the angle bisector vs the path perpendicular to the orientation of the line.]

As a complementary experiment we let the line, again in a diagonal orientation, travel through a simple diagonal-symmetrical quadrilateral (figure 18). Here the *heights* of the two path segments together constitute a straight line (indicated by a dashed line) and the bisectors lie obliquely with respect to each other. Despite an assimilation of the motion direction in the two path segments, a bend is noticeable in the course of the motion, whose sense, if not its magnitude, is in accordance with the angle formed by the bisectors. Owing to assimilation however, it is necessary for the quadrilateral aperture (as in figure 18) to have a shape sufficiently different from the parallelogram for the sharp bend to become clear.

Part 3. The mutual influence of motion processes in different parts of the path and in neighboring apertures

§10. The assimilation of the direction of motion in different parts of the path

Again we must consider the mutual assimilation of the motion directions in different parts of a path (this was described before in Section II §1). An assimilation of the temporally earlier motion with the later one occurs, and vice versa. As should be obvious from our description, the curve of perceived motion depends on the importance of the participating path segments, and not on their temporal order. One should not consider this process merely from a static figural viewpoint—for example, by referring to the fact that the whole aperture is visible while the line travels through the first part of the path, and could therefore act upon the motion process in this path segment by assimilation without the influence of the line motion in the subsequent segment of the travel. An argument against this interpretation is the dependence of assimilation

on the speed of the line. For high speeds we seemingly observe an effect of temporally later events on temporally earlier ones. This may only be possible within very narrow limits, since for slow speeds assimilation is absent, as reported before.

This is not the first time that it is assumed that an effect exists of a temporally later stimulus process upon a central process corresponding to a temporally earlier stimulation. E Rubin⁶ applies it to explain the displacement phenomenon reported by Fröhlich (see also Section II §7) and proves it experimentally.

This hypothesis, according to which assimilation is based upon a cooperation between temporally earlier and later actual displacement processes,⁷ is supported by the ‘experiment with the four circles’ described below. First, however, we report two preparatory experiments.

§11. *The direction of motion in a circle*

A straight line is always perceived to move perpendicular to its orientation when it passes through a circular aperture. At first, one may assume that this is exclusively the result of the absolute direction tendency for an [infinite] line to be seen to move perpendicular to its orientation; [one might suppose that] a figural direction tendency would not derive from an aperture with a curved edge.

The following experiment proves the opposite. A line is displaced behind a screen with a vertically oriented, rectangular aperture and an adjacent circular aperture (figure 19). For such closely neighboring apertures a tendency exists for line segments that are visible in both apertures simultaneously to move in the same direction. At the instant when the line is passing through the rectangular aperture, just before it appears in the circle, the line is moving vertically; when passing through the circle, the line would have to move diagonally. Which unified motion occurs? The line passes through the circle

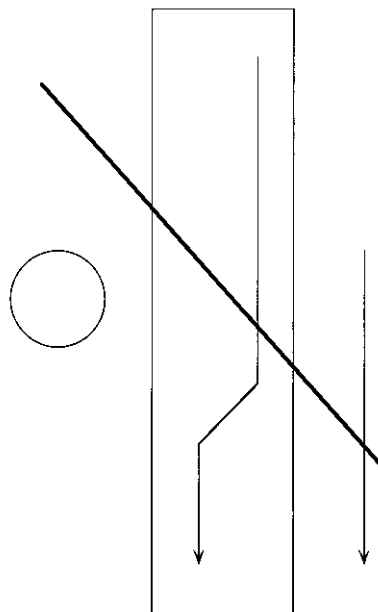


Figure 19. Motion through an elongated and a circular aperture. As the line becomes visible through the circular aperture, its direction of motion through the elongated aperture is seen to change from vertically downwards to oblique. The fact that the circular aperture changes the perceived direction in the elongated one (and not vice versa) suggests that the oblique perceived direction of motion through a circular aperture is not caused by the tendency of the line to move perpendicular to its orientation, but rather is a result of the figural effect of the aperture of shape.

⁶ E Rubin, 1938 *Psychol. Forsch.* **13** 101.

⁷ These are slight time differences whose order of magnitude is in accordance with what could be expected from earlier experiments. More in §2 in this section.

diagonally and in that way changes its vertical motion in the rectangular aperture and moves abruptly leftwards. Thus, strangely enough, the diagonal direction of motion prevails over the vertical one (parallel to the edges), within the rectangular aperture. This would not be the case if a figural direction tendency was not derived from the edges of the circular aperture.

While passing through a circular aperture a marked expansion and contraction of the line can be observed, which appears absolutely symmetric if one does not happen to fixate the edges. The path traversed by the midpoint of the line (the center of the internal motion) coincides with the direction perpendicular to the line orientation, and this coincidence probably causes the stability of the direction in the circle, of which the experiment described in this section provides an example.

§12. *The experiment with four circles*

In the following experiment the screen carries four circular apertures of equal size, which, as shown in figure 20, are arranged in a horizontal row. Unlike in the previous experiment, the orientation of the line (a) is chosen such that it has already left one aperture when it becomes visible in the following one. Between its passages through each aperture in isolation it is invisible for a brief moment. One can see this process in a multitude of ways. In one extreme, it appears that each isolated circular aperture is passed through successively by a short line in an oblique direction. Each aperture is passed by a different line that is entering the field with a small jump, grows, shrinks, and ceases to exist. In the other extreme, one perceives *one* line moving uniformly in the horizontal direction (as if there had been one very elongated horizontal aperture instead of four small separated ones) and in that way the line becomes visible in the four screen apertures. In between there are numerous transitional perceptual forms. It can happen that a line is perceived to travel through each aperture obliquely from top to the bottom, and, in the brief period in which it is invisible, moves with a jerk upwards to attain the new starting point for the oblique motion. It can be that *one* line is seen to move horizontally, but always slides obliquely in the apertures. Only one version never seems to occur spontaneously, that one which is closest to the objective facts,

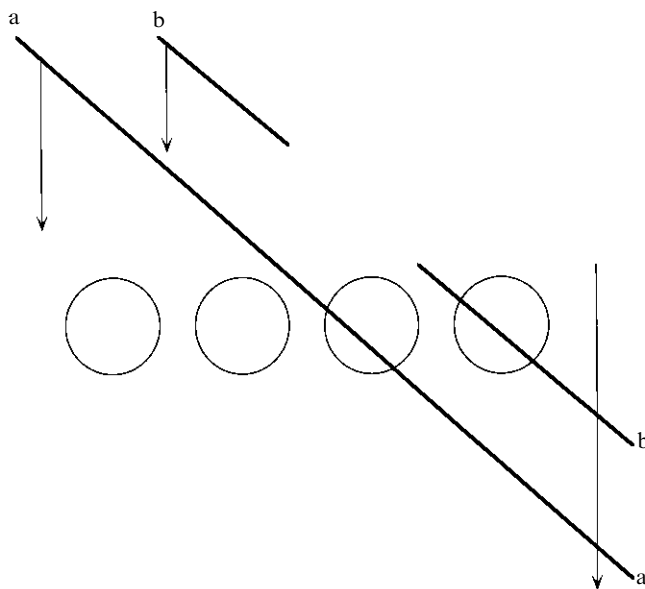


Figure 20. Four circular apertures—an experimental setup designed to demonstrate that temporally later parts of the motion can (perceptually) affect temporally earlier ones. In setup a, the line is seen to move horizontally through all four apertures. In setup b, a line is seen to pass only through the first and third apertures, and its perceived direction is often oblique.

namely that an extended line of the length of the row of the apertures moves uniformly obliquely, such that gradually different parts become visible in the different screen apertures. 'Invisible existence' over too large an extent would be required for this interpretation; after all, through each aperture different parts of the long line would be visible.

Characteristically, for uniform horizontal motion, nothing can be sensed of the small jump or jerk, which accompanies the entrance of each line into the circular aperture for oblique isolated motion (Fröhlich displacement). Hence, the conditions for the occurrence of Fröhlich's phenomenon should probably not to be sought solely 'externally' in the processes of the stimulus configuration, as was done until now. The Fröhlich displacement does not occur whenever a sufficiently fast moving object becomes suddenly visible; apparently, it is necessary for it to be a perceptually *new* object. In our case it turns out that the perceived form of existence of the line in the period during which it is invisible governs the occurrence of Fröhlich's phenomenon. In the first of the four circles it also occurs for horizontal motion.

Our account is based upon the spontaneous reports of the subjects, since an instruction to pay attention to these phenomena alters the perceived form of the process. Directing the gaze towards the location at which the line enters into the second or the third circle, and expectation of this moment, elicit oblique motion.

For us it is most important whether the motion of a line occurs in a horizontal or oblique direction, and that clearly depends on 'attitude'. What probably matters most is how strongly the four circular apertures belong functionally together to form a horizontal stripe. Also, prior exposure [hysteresis] plays a major role, ie the tendency for re-occurrence of a previous motion percept. Something of the organization corresponding to a particular form of motion is retained between presentations and has the effect that a motion form similar to the previous one occurs. Apart from that, the perceived direction of motion clearly depends on the speed of the line. For slow speeds, oblique motion of isolated lines is perceived, whereas at higher speeds the horizontal motion usually occurs immediately. For most subjects it is retained [owing to hysteresis] even after the speed is once again reduced. A perception of oblique motion returns only after a pause, or in connection with yet another [third] identity impression: the same line is seen to move through all apertures, yet it slides obliquely in each of them. Once present, identity of the line segments visible in the four apertures seems to produce a maximal aftereffect [hysteresis]. However, it is not the case that the horizontal motion only occurs as a fatigue of the oblique motion form, that is as a consequence of one or several previous presentations. We were able to find cases where immediately, at the first presentation, horizontal motion was perceived, and then, after the speed was reduced, oblique motion was seen. Finally, there are also subjects who always perceive horizontal motion above a critical speed and oblique motion below it if there is a longer time interval between the single presentations.

This dependence on the speed we explain exactly the same way as that observed for the assimilation of the direction of motion in different parts of the aperture. That is, the appearance of horizontal motion ought to depend, among other things, on whether the passage through a following aperture can possibly influence the perceptual process corresponding to the passage through a previous aperture; most likely this is only possible within a brief time period.

E Rubin calls it 'processing time'. In his paper "On the theory of stroboscopic motion", Köhler assumes that, of the processes corresponding to two stimuli that elicit stroboscopic motion, the first one has not yet faded away when the second one appears.

We found a critical speed of approximately 6 cm per second. The circular apertures had a diameter of 2.5 cm, their distance apart was 1.7 cm. Therefore, the path from one midpoint to the other one was 4.2 cm long; it is traversed in 0.7 second. The line is invisible on its path each time for 0.65 cm (this is the distance between two neighboring line-parallel tangents at adjacent circular apertures) that corresponds to 110 ms. This time period can also be bridged as the interval of stroboscopic motion; but even for stroboscopic motion it is close to the upper limit. From his experiments with Fröhlich displacement Rubin calculates a processing time of 150 ms.

The following experimental variation demonstrates that, for horizontal motion in one of the circular apertures to be perceived, it is not enough that the entire four-piece aperture is visible, and that a line passage in horizontal direction has taken place shortly before. On a paper tape that is a bit longer than usual, there are three lines at identical separations, and two of them are identical to the line employed in the previous experiment (a in figure 20), while the third one, b, has the same orientation as the other two but is interrupted such that it becomes visible only through the first and the third aperture of the screen. While the first two lines are perceived to yield horizontal motion during their passage, the interrupted line that just follows them frequently appears to move obliquely through both apertures. The lack of the line passage in the second and the fourth aperture prevails despite the constant aperture arrangement and against the aftereffect [hysteresis] which is present and which is directed towards a horizontal course of motion; this demonstrates nicely the effect of later parts of the motion passage on temporally earlier stimulation.

It remains to be said that the perceived motion depends also on the visual size of the constellation. Small size of the aperture constellation favors the appearance of horizontal motion. The small aperture size probably increases the overview of the entire figure consisting of four circular apertures. For the reported main experiment, the dimensions apparently lay close to the upper limit for horizontal motion to occur at all. We therefore conducted this experimental variation at a reduced scale of two fifths, and in that way indeed favored the occurrence of horizontal motion. Conversely, enlargement leads to a complete lack of horizontal motion. A fivefold enlargement of the relevant dimensions can be accomplished by presenting the constellation in the main experiment with arrangement ii. Then the horizontal motion never appears spontaneously. As mentioned before, arrangement ii enlarges only the perceived size of the constellation compared to arrangement i; the visual angle remains constant; the retinal relations are therefore the same in both experiments.⁸

§13. *The motion of contours in apertures of different shapes*

In the experiments described so far, the straight, homogeneous form that carries the 'line motion' was represented by a neatly drawn straight stroke up to 1.5 mm wide. We found that the experiments produce the same outcome when, instead of a line, one uses a contour that is formed by two different bright areas, eg a white and a black one. Through the instruction to the observer to describe its direction of motion, it attains the same property of being a real thing that a line set off from a homogeneous background possesses by itself. If *two* contours are visible in a rectangular aperture, by using as a stimulus the drawing of a moderately wide black stripe, then two cases are possible. The contours may undergo a change in direction due to the shape of the aperture isolated and independent from each other, or together in rigid connection with each other.

Section III. Experiments on the motion of straight lines after features with an objective direction of motion were introduced

§1. *A line with an ending in the field*

[To understand the motivation for the following section, recall that both the aperture and the background of the moving line were white. This might suggest that the effect of the aperture may be merely one of making the line seem to end abruptly (as would be the case if the setup were simulated on a computer screen). However, Wallach used a physical setup: in the following section he shows that the observers were *aware* of the line continuing behind the aperture. However, in spite of this knowledge, the aperture borders (and shape) still determined the perceived direction of motion.]

He who finds the preceding description of such simple experiments too lengthy might want to argue that our line in the aperture behaves no differently from a line segment that moves in a homogeneous field and continuously changes its length in just such a way that it mimics precisely the changing extent of the endless line that is visible in the aperture. We would agree with him and say that we also consider this

⁸ Compare Jacobs *Psychol. Forsch.* **18** 98 ff.

as likely, but would like to see the experiments conducted. We thought that for a single line (as opposed to the line pattern [see Section IV]) it was characteristic that the parts hidden behind the screen play a rather minor role, although they may be perceptually present in some cases. That's not what I meant, our adversary might interrupt us: according to his opinion, the two experimental setups would give entirely the same results. In our experiments we may not even be dealing with 'straight lines' in the aperture, which would have to be infinite after all, as stated in the introduction. With respect to the stimulus, the lines would end at the aperture edges. The two experimental setups differ merely in that in our case the aperture contour is visible in the field, and he really could not attach great importance to that. Of course, our subjects *would know* that 'really' the line is extending behind the aperture border, which is clearly visible as such, and it is in this sense that the occasional descriptions of the subjects, that the line disappears behind the aperture border, ought to be understood. On no account could the line be *seen* behind the screen. The alleged 'perceptual existence' of an invisible object, which could only come about through such knowledge, surely would be a matter too vague to make a claim based upon it that we are dealing with endless lines in the aperture.

In opposition, we could recall the behavior of the line in the four circles; however, we prefer to describe yet another new experiment. A line is shown, whose ending becomes *visible* when passing through the aperture. In contrast to the experiments described before, here the objective motion direction actually matters (and not only the sense of motion), because it determines the path that the [visible] line ending travels in. In the description of the experimental conditions we therefore must specify the direction of motion of the tape and the orientation of the line on the tape: the motion direction is vertically downwards, the line is tilted away from the horizontal by an angle of 30 degrees, and it ends in the middle of the tape. The screen with a square aperture is positioned in front of the tape such that the path of the line ending runs close to the left aperture edge and parallel to it from the top downwards, as shown in figure 21. The experimental run goes like this: the line enters the aperture in the upper right corner and becomes visible, its length increasing, as is usually the case in the corner of the aperture—until the ending appears at the upper border. Since the tape moves objectively downwards, as soon as the line ending appears the visible length of the line remains constant until it has reached the right bottom corner, then becomes shorter and shorter, finally disappearing at the lower aperture border.

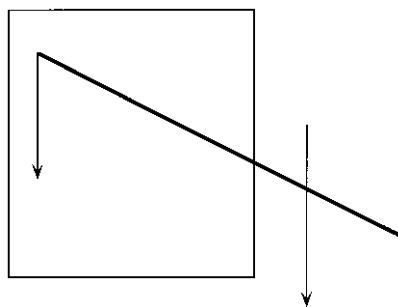


Figure 21. A line with an ending in the field compared with a line that terminates at the aperture border [figure 22]. The objective direction downward is shown by the arrow. Only the part of the line within the aperture is visible. The line enters the aperture from above. In its initial travel through the corner of the aperture it appears to move obliquely, then abruptly downward when the free line ending becomes visible.

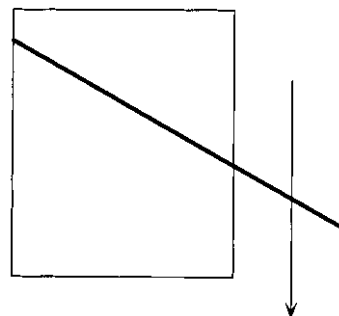


Figure 22. The line [terminating at the aperture border] first appears to move obliquely, then appears to turn downward when the line ending on the left intersects the vertical aperture edge. However, unlike the experiment of figure 21, the perceptual transition from oblique to vertical motion is smooth and gradual.

We conducted the following experiment for comparison. The line moved through a slightly narrower aperture whose left border just hid the path of the line ending. The perceived direction of motion was, as expected, oblique–vertical–oblique, or sometimes vertical until the end (figure 22). It did not turn out fundamentally differently from the previous experiment when, in the wider aperture, the line ending passed through the field. As long as the line ending is invisible, the line appears to move in accordance with the aperture obliquely (unless the perceived motion runs horizontally because the observer directs his gaze towards the upper border) and then vertically, until the line disappears. And nevertheless: what an entirely different sight! The change in perceived direction when the line ending is visible takes place with such a sharp jerk that one might wonder afterwards whether one sees the line moving downwards intact. For the pure line motion (ie for the hidden end), on the other hand, the change in perceived direction takes place in a smooth curve without the line ‘bumping’ against the newly intersected aperture border when it passes the upper left corner, even when through fixation of the border a change in perceived direction of a full 90 degrees occurs. In contrast, in the experiment with the free line ending, the line abruptly ‘bounces off’ as soon as the free end enters the aperture. Many subjects perceive it as moving a bit further to the left than to the point where the end appears and then rebounding, as if it had hit an elastic wall. All of this appears very odd, and most of the observers could not help laughing. We suspect it is not because there was nothing visible for the line to hit and rebound from—the entire process strikes a person as so out-of-this-world that this is not even noticed at first. Rather we believe that the oddness is due to the abrupt situational change that one witnesses. There is a sudden transition between two motions that have an entirely different character. Specifically, as it becomes obvious now through direct juxtaposition, while the line motion in the corner of the aperture is soft and a little bit vague, the line with the ending goes rigid and directly downwards. It now seems as if the perceived direction of motion of the line is determined completely by the motion of its visible ending.

A slight experimental variation confirms this: we greatly reduced the height of the aperture so that the line has already passed the lower right corner when the ending entered the field. Then, if the path of the line ending is covered by the left aperture border, the result is a direction curve with a horizontal intermediate piece, and when a higher speed is employed, an almost horizontal assimilation curve. However, if the experiment is conducted with a visible line ending, then, when the line ending appears, the perceived direction of motion is vertical as in the previous experiment. The motion of the line is therefore entirely changed by the visible ending; it adopts the direction of the path of the visible line ending. The line behaves as if the identity of the visible line ending is represented in a completely unalterable manner. Functionally the line is scarcely more than an appendage to the ending, which performs the motion and carries the line with it.

This experiment demonstrates with utmost clarity the difference in behavior between a visible line ending and the termination of the visible line segment at the aperture border; at the same time it points out the entirely different character of pure line motion [ie the motion of the featureless parts of the line] and of a motion process whose direction is determined by the kinematics of the stimulus constellation [as the motion of the line ending is]. Line motion and motion in a determined direction are processes so different that the abrupt change from one to the other in this experiment has the character of a joke.

§2. *A line on an ornament pattern*

We have already mentioned that occasionally in arrangement i the texture of the paper allows the objective motion of the tape to have an effect. If in that case the line motion due to the aperture shape does not agree with the objective motion, then two sorts of

behaviors may occur: either the line is seen to travel along a path determined by the aperture shape, independent of the motion of the background it is drawn on, or it is diverted from its direction and captured by the motion of the background. In the former and more frequent case, the motion of the paper doesn't play a perceptual role after a few repetitions of the passage. Following this occasional observation we have developed an experiment in which the objective motion direction is represented by a rich pattern and cannot be overlooked. In this case we manufactured a tape made of endpaper (as in a book), which was printed with a small ornament pattern, and on it we drew a line of a 40 degree tilt. The very conspicuous pattern of the background frequently caused the line to move in the objective direction of motion. In a horizontally placed 'parallelogram in a special orientation' [Section II §2], however, the line and the pattern executed separate motions for most subjects; while the pattern moved vertically downwards, the line slid across it in the horizontal direction in accordance with the shape of the aperture. The two motions seemed to occur in two different layers, even though there was no physical difference in depth.

Separated motion frequently occurs also in a circular or triangular aperture. Here it is probably the change of the visible length of the line during passage through the aperture that favors its detachment from the patterned background. The line's change of length does not fit into the rigid motion pattern, since the pattern is perceived as independent of the incidental aspect provided by the aperture (see also Section IV §2), while the changes a line undergoes in the aperture appear to be, to a great extent, its own changes. This functional dissimilarity in the rigidity of the pattern and the expansion of the line could easily result in, or facilitate, a separation of line and pattern in the motion process.

Furthermore, it should be noted that the same experiment does not yield separated motion for objectively horizontal motion of the pattern—the apparatus including the screen is rotated (in arrangement ii) by 90 degrees. In this case the line always remains attached to the pattern and moves horizontally with it. It emerges from behind the leading border and disappears behind the other one. Here we see a case of the distinction of horizontal motion, which we will encounter in many forms, and in this way it differs from vertical as well as from oblique motion.

§3. *Line and point*

Objective motion can also be represented by a conspicuous point, placed on the line (we used such a point with a diameter of 1 cm). Only rarely, however, does this lead to a perturbation of the perceived direction of line motion as determined by the form of the aperture. When this occurs, the point takes the line along in its objective, vertical direction of motion. Then it appears to stick firmly to the line as it is when it is viewed while stationary. In most cases, however, the line is perceived to move as determined by the aperture shape, while the point, sliding along the line, moves downwards. This experiment directly illustrates the exchange of objectively identical parts of the line among one another, which takes place continuously in the perception of line motion (compare Section II §8). For sure, the point marks an objectively identifiable location on the line. For example, in the constellation of figure 23, if the line is perceived to move horizontally as determined by the aperture shape (while the objective motion is vertical), then the visible segment of the line, which remains a perceptually identical unit, is displaced upwards continually and uniformly in the direction of the line orientation: upwards relative to the objective-physical line elements, and therefore also with respect to the point. The point is perceived to slide along the line downwards. Moreover, it is seen to move obliquely in the direction of the line orientation. This is curious since it ought to move vertically downwards corresponding to its objective motion. Clearly, we are dealing with a case of a separation of systems.⁹

⁹ Compare Duncker, 1929 *Psychol. Forsch.* 180 ff.

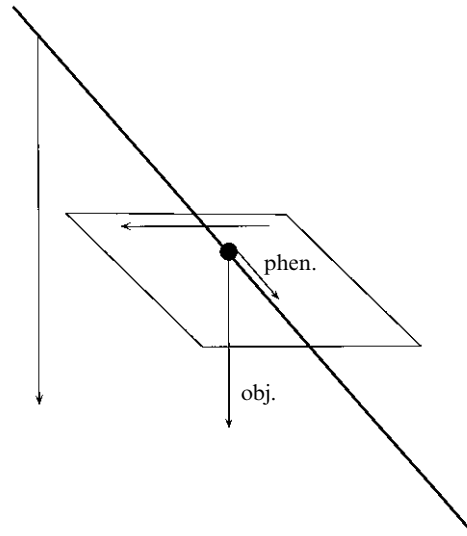


Figure 23. Line and point. Objectively the line moves downwards and is viewed through a parallelogram aperture. In some cases subjects report that the line and point appear to move downwards. More often, the line appears to move horizontally (in the direction of the line terminators) while the point appears to slide along the line, down and to the right (arrow labelled 'phen.' for phenomenological).

While the motion of the line is related to [the reference frame of] the aperture, the motion of the point is seen exclusively in relation to the line owing to the immediate contact of point and line. As a consequence, the 'absolute' motion direction of the point, namely that relative to the aperture, is not at all present in perception. Perceptually the point moves along the line—which has an oblique orientation—and the line moves perceptually horizontally, such that a vertical motion of the point relative to the aperture would result. This is, as pointed out, not perceived; only the motion of the point relative to the system 'line' is perceived.

The processes remain perceptually the same when the point is not drawn right on the line but, for example, at a distance of 1 cm. Even then the point moves obliquely in the direction of the line orientation. In these experiments the point represents the objective motion of the tape in terms of the stimulus but not perceptually, as the ornament pattern does (§2). Here the aperture field is—in contrast to the experiment with the ornament pattern—dominated by the line motion, and compared to it the point acts like a surrounded isolated object.¹⁰

The percept is influenced by the motion of the field that is directed towards the left, in the sense of induced motion; it is subject to the tendency to be seen as moving in the opposite direction (horizontally to the right). From this impulse, and the objective motion downwards, the motion obliquely downwards and towards the right results.¹¹

§4. *The dashed line*

The two alternatives, separated motion determined by the aperture shape or common motion, which were observed in the experiments of §2 and §3, will always exist, at least in principle, unless the moving line by itself carries features of objective motion, as is the case when the line ending is visible in the aperture. But even in such a case motion determined by the aperture may occur; for this to happen, the directional tendencies

¹⁰ Compare Duncker, 1929 *Psychol. Forsch.* 202.

¹¹ That this motion runs precisely parallel to the line is already suggested by the arrangement. Objectively, the point has the same distance from the line during its entire passage.

in favor of it must be very strong. Consider the case of a dashed line.¹² Each of the dashes that the line consists of is capable of conveying the objective motion. Yet, if a tilted dashed line moves objectively vertically downwards behind a horizontally oriented rectangular aperture (figure 24), often motion parallel to the [long] aperture edges is perceived. The line as a whole moves horizontally, while all the dashes that make up the line slide obliquely downwards as in an invisible tube. Again, separation of systems is present, quite analogous to the case of the point sliding along the line.

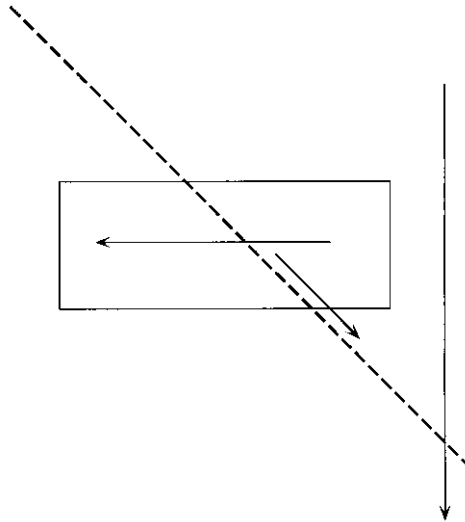


Figure 24. The dashed line. The motion of the line objectively downwards through a horizontal aperture is denoted by the vertical arrow. Two perceptions of the direction of motion of the line are reported: (1) downwards, consistent with the objective direction, and (2) horizontal motion consistent with the intersections of the line with the aperture edges. When horizontal motion of the line is seen, the dashes appear to slide obliquely along the line.

It is interesting, that now one and the same object falls into two systems. The line as a whole moves relative to the aperture, the dashes constituting the line move relative to it.¹³ The objective and the subjective-relative vertical motion of the dashes divides into two systems in experience. The two emerging motions, the horizontal one and the one directed obliquely downwards, are related to the vertical one like two components to their resultant.

A perception of pure 'line motion' [perpendicular to the line orientation] arises with certainty if one accumulates the factors favoring horizontal motion. To this end one rotates the stimulus tape in its plane (arrangement ii), until the dashed line lies vertically (the objective motion direction is then oblique), while the aperture remains in its horizontal position. Then the direction parallel to the aperture borders and the direction perpendicular to the line orientation are in agreement. As a result one always perceives a row of dashes moving vertically and at the same time being displaced towards the side.¹⁴

¹² Further cases given in Section IV §12, §13, §14.

¹³ In principle, the same form of separation of systems occurs for the rolling wheel. Here the single discriminable points of the wheel perform a uniform rotatory motion whereas the wheel as a whole is in translation. (Rubin *Z. Psychol. I* **103** 384–392). Compare also Oppenheimer *Psychol. Forsch.* **20** 23, §7.

¹⁴ We shall separately report the interesting appearances observed during passage of a zigzag line through an aperture, in which the theme of line motion plays a crucial role too. [This is discussed in H Wallach, 1976 *On Perception* pp 215–216.]

Section IV. The motion of line patterns in an aperture

Part 1. 'Pattern motion'

§1. *The stability of a grating pattern*

In the experiments described previously, the tape carried ordinarily only one line; only occasionally two were drawn on the tape, so that the pauses between single presentations did not become unnecessarily long. But then the pauses were long enough for the presentations to be isolated and well-separated. If the number of lines on the tape is gradually increased, changes in the character of the passage of the single line through the aperture occur owing to the altered temporal interval. Finally the case arises that several parallel lines are visible in the aperture simultaneously, and if these grow more numerous, an entirely new impression emerges. No longer are isolated lines visible in the aperture, but a line *grating pattern* fills the field. This section will deal with the behavior of line grating patterns. Here we define a line grating pattern not based on its perceptual impression, which the drawing on the stimulus tape elicits, but functionally: thus, a line behaves differently during passage through an aperture, if it is a member of a pattern of parallel lines, compared to when it is isolated (or travels independently of the neighboring lines) in the aperture field. Through the rectangular aperture shown in figure 7, an oblique line moves in a direction indicated by the curve in the figure. On the other hand, a line *grating pattern* consisting of lines of the same orientation and traveling through the same aperture (figure 25), is seen to move uniformly in a horizontal direction. Suppose this would not be the case, and each of the lines constituting the pattern were perceived to travel through the rectangle along the curve known to be traced by the single line; then the single lines would one by one undergo the change in direction since they pass successively corners A and then B. The turning points are marked as dashed lines in figure 25. Consider the neighboring lines labeled with numbers in the figure: the line labeled 1 would, for example, possess a horizontal direction of motion; line 2, on the other hand, an oblique direction until it would have passed the turning point; then it would run horizontally as well; and its neighbor line 3 would have yet a different direction. The aperture field would thus be divided into three zones which might be internally consistent, but certainly of different perceived directions of motions. These would be adjacent at the turning points, and each line in isolation would belong to the single zones in succession. As a result of the uniform perceived direction of motion of the grating pattern in the entire aperture,

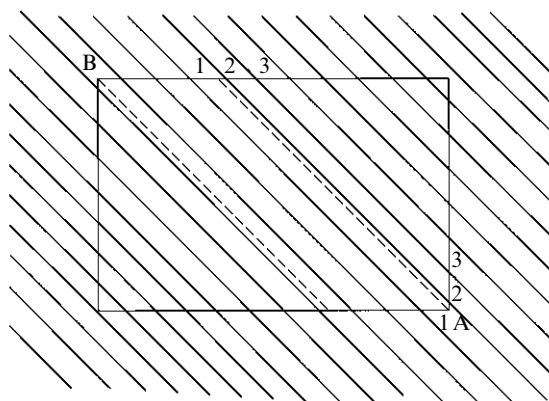


Figure 25. Line grating pattern in a rectangular aperture (only the portions of the lines within the rectangular aperture were visible). The objective motion of the grating pattern is vertically downward, as the single line of figure 7, but the perceived direction of motion is uniformly horizontal. While the line labelled 1 has both terminators along the horizontal aperture boundaries, lines 2 and 3 have one terminator on the upper horizontal edge and the other on the right vertical edge. Their perceived motions were all the same, however (see text). This stimulus has been called 'the barberpole illusion'.

these breaking points are avoided and each line is in the same relation to its neighbors throughout its entire passage. In such cases, when the lines are perceived to move in a uniform direction through an aperture that would cause an isolated line to change its perceived direction, we call it *pattern motion*.

Whether stable pattern motion emerges depends not only on the mutual perceptual distance between the lines. The aperture has to be sufficiently wide so that a sufficient number of lines are simultaneously visible. Furthermore, it must allow the lines to be visible to a sufficient extent; the pattern motion stability depends crucially on the relative lengths of the intermediate fields bounded by two neighboring lines.

We interpret the phenomenon of pattern motion in the following way: the single lines are more intimately connected with each other in the pattern motion, and this connection is probably of the same nature as that we assume between members of a stationary selected group. Thus, the single lines partly lose their object quality and together constitute a novel form that is characterized by its motion as a whole.

§2. *The line grating pattern and the edge of the aperture*

This new object, the pattern, differs functionally from the single line in other respects as well, namely in its existence beyond the aperture edge. Perceptual descriptions about this are difficult, if only because of the rapid change of impressions. Nevertheless we claim that a moving line grating pattern, in contrast to a single line, extends [perceptually] beyond the aperture border from the beginning, and verify this claim as follows: a line pattern in the ‘parallelogram in a special orientation’ is perceived to move for an extended period unaltered parallel to the intersected borders. If one rotates the entire constellation (arrangement ii is suitable for that) such that the lines of the patterns are oriented horizontally (figure 26), then frequently vertical motion is perceived instead of the aperture-determined oblique motion, ie a motion pointing outside the aperture. This does not happen in the case of a *single* line. To understand this experiment we note again that for vertical motion the absolute tendencies, perpendicular to the line orientation and parallel to the principal directions of space, coincide, and that they can prevail over the effect of the aperture edges. Because of the weak effect of the

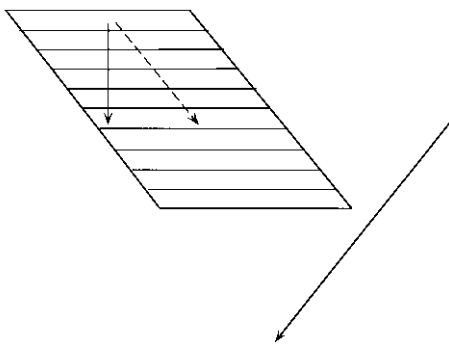


Figure 26. A line grating pattern within an aperture may appear to move perpendicular to the grating orientation. Through a parallelogram aperture, a grating with horizontal lines is perceived to move in a vertical direction downwards, as indicated by the solid arrow. Such a motion direction would never be seen with a single line and it is not observed at other grating orientations. The motion direction of the line terminators is oblique down to the right, as indicated by the dashed line. The objective direction of motion of the tape is oblique down and to the left as indicated by the long arrow.

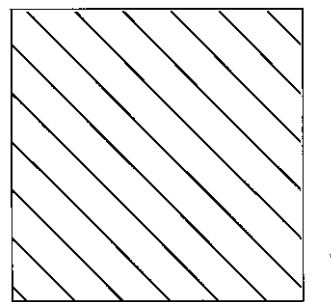


Figure 27. Oblique line grating moving in a square aperture. This experiment demonstrates the effect of ‘saturation’. The grating moves objectively downwards (arrow), and is perceived to move (after a brief initial period of perceived oblique motion) first horizontally and then vertically, and then perceived horizontal and vertical motions alternate in an irregular succession.

principal direction tendency (vertical and horizontal) for some subjects, the experiment does not turn out always like that. This, however, does not diminish its importance. For the single line in the same constellation, the experiment *never* turns out like that, as mentioned before; the line moves always in the direction parallel to the edges.

The fact that the line pattern, as opposed to the single line, tends to be perceived as extending beyond the aperture borders is also evident in the following phenomenon. If an oblique line pattern moves behind a square aperture (figure 27), then at first oblique motion is seen (in most cases only briefly), and then vertical or horizontal motion occurs—in most cases horizontal. Already the first phase is different from the motion of a single line—although it would also appear to move in an oblique direction. A single line is seen as growing while moving through the corner where it enters the aperture and as shrinking in the opposite corner (see Section II §7); the lines of the pattern, on the other hand, seem to emerge from behind the aperture edges and disappear behind them again in the second half of their path, when they leave the aperture. Since, for the oblique motion direction, entrance or exit of lines occurs all along the aperture border, the pattern obviously ‘exists’ on all sides beyond the aperture edge.¹⁵

This relation changes when, after a short while, perceived motion parallel to the edges (horizontal or vertical) occurs. Then the lines of the grating appear to terminate at the borders parallel to the direction of perceived motion (eg at the top and at the bottom for horizontal motion). They only continue to exist perceptually beyond the other two edges, where the pattern is perceived to enter and then exit the aperture. In this case the motion has, as opposed to the oblique phase, more the character of a fixed track. Typically, when motion is perceived to be in the horizontal direction, such a perception of motion parallel to the intersected edges does not require even one line of the pattern to intersect the two leading, opposite edges of the aperture simultaneously. This works because the lines are firmly bound to each other, forming *one* pattern, which is ‘led’ as a whole.

Part 2. Saturation

[In this part, Wallach describes the phenomenology of prolonged viewing of moving line patterns (gratings) in an aperture. This stimulus is richer than the single lines (described in Sections I–III) and can lead to more than one percept. The description of percepts that emerge during prolonged viewing will be continued also in Parts 3 and 4.]

§3. *The turning of the motion*

With, for example, oblique objective motion towards the left and down, an experiment with the constellation of figure 27 takes the following course: first oblique motion perpendicular to the orientation of the lines is perceived, which can last from 1 up to 10 seconds, and then in most cases the horizontal motion which was previously described is perceived. This phase lasts somewhat longer than the first one and then gives way to perception of vertical motion. After a brief period, however, the lines are again perceived to move horizontally, and in this manner vertical and horizontal motions alternate in irregular succession. Deliberately we no longer talk about different motion *directions*, but of distinct *motions*, since perceptually these are entirely different motion processes alternating with each other. The change in the phases occurs every 4 or 5 seconds on average (with large individual differences). Perception of vertical motion lasts in most cases for a briefer time than that of horizontal motion. After prolonged exposure, the frequency of the phase change increases. These changes in motion are perceived to have quite an objective character, and it is hard to convince many subjects that objectively different motions are not being presented. Some of them are in an exceedingly contemplative mood after the experiment, and for the

¹⁵ Compare the description on the behavior of the ornament pattern in Section III §2.

experimenter it is again and again an adventure of curious fascination if, say, the subject describes vertical motion, while he himself, observing as well, is just perceiving completely 'objective' horizontal motion.

The transition from one motion percept to the other occurs in several different ways. For many subjects, the phases plainly succeed one another and some report perceiving a rotation from the horizontal to the vertical, or conversely. For others complete confusion of the motion briefly occurs and then the new motion process emerges through self-organization. Some observe for a brief period of time an intermediate phase of oblique motion. Presumably these impressions depend on individual differences in the stability of the pattern.

Slowly one learns how a specific motion process can be elicited at will, for example through fixation of an aperture border. Then one is able to put into action the other phase, before the change of motion has occurred of its own accord. But it is impossible permanently to hold onto a single motion process. An effort in this direction does not even have the effect of prolonging the intended phase compared to the other ones.

§4. *The disintegration of the grating pattern*

After a couple of minutes of observation, the impression of rigid motion falls apart. One perceives horizontal and vertical motion in the aperture side by side, so that one of them occurs in the first path segment, the other one in the second. Often a sharp border is seen to run in the vicinity of the diagonal parallel to the lines, often a rotational motion is found in the aperture field. The rule is that each of the lines now moves like a single line when the direction of gaze is pointed towards the aperture edge, and the experience corresponds to what we would have to expect if the lines had no figural connection with each other (compare Section IV §1).¹⁶ Thus we assume that the binding of the lines to each other, which supports pattern unity, is destroyed to a large extent in this later phase, and we refer to it as *pattern disintegration*. However, the perceived motion in this phase cannot be compared with the perceived motion of a single line. The process provides an awkward, even painful sight and almost creates a mood that makes any comparison with processes from the other experimental period impossible. One is not able to visualize a different motion form for the purpose of comparison. The experiment ends with unbearable hurly-burly in the aperture.

§5. *Figural changes of the grating pattern*

Even before the disintegration of uniform motion, subjects frequently describe changes of the line grating pattern; no longer is a uniform area of the pattern perceived, but instead of it 'planks'. Neighboring lines become contours of the plank spacing and the planks have the character of an object. The planks can lie adjacent to each other without any gaps, such that each line has a twofold function as a contour, or they can be separated by a spacing, and sometimes a version occurs where a single line and a plank succeed each other in alternation. These versions alternate as well, but a correspondence with a change in perceived motion cannot be shown. Moreover, these appearances are clearer if only *one* type of pattern motion is perceived. If a constellation allows only for one version of rigid motion, then the divided motion, if possible, happens earlier and is less unpleasant.

§6. *The cause for the change of motion*

How can we interpret the changes in the perceived motion of the line grating pattern? During transition from perception of oblique motion to the edge-parallel one, the line grating pattern adjusts itself to the aperture. At first it appears as if it extends beyond the aperture borders around all sides and appears to move independently of the shape of the aperture, perpendicular to the orientation of the lines. However, when the perceived direction of motion is determined by the aperture border, the line grating pattern is *led* by the pair of aperture edges parallel to their direction, and the lines are now seen to

¹⁶ The corresponding phase in the rectangular aperture shows the typical tripartite motion of a single line.

end at these edges. From figural reasoning, two edge-parallel motions are possible in the above example—along the vertical and horizontal edges; they are functionally equivalent to each other and are always realized in alternating succession (compare Section II §1). Which one is adopted first may be determined ‘by chance’. But for what reason is the once adopted direction forsaken, and why do the motion processes change continuously? One can state a number of occasions at which the perceived direction of motion changes, eg a blink or a change in the direction of gaze (in particular the gaze directed towards an edge that, together with its opposite, will lead the pattern). But in view of the inevitability with which the change prevails against all efforts to hold on to the same motion process, all those occasions ought to be judged as mere ‘opportunities’, at which the true cause takes effect. This [true cause] we seek in the continuous nature of the perceptual motion process itself. “In some instances, sensory organization seems to change spontaneously, ie in the absence of any outside influence, simply because processes which pervade given parts of the nervous system for some time tend to alter the condition of the tissue in question.”¹⁷ In this way Köhler explains the periodic perceptual changes in figures that allow two different versions of figure-ground interpretation. Similarly, we interpret the process of the motion change. Moreover, in our experiments we even find a strong argument for Köhler’s hypothesis.

The occurrence of, say, horizontal motion (when the pattern is moving objectively vertically) can be prevented for a long time by allowing the line endings to be visible in the aperture (figure 28). If one presents this constellation for a prolonged time period, then two possibilities can be seen: vertical motion, or mixed motion, whose main component is vertical as well. If one then, without interrupting the presentation, displaces the screen a little bit towards the right such that the line endings are hidden, then immediately the horizontal motion ensues, which only *after a prolonged period of time* yields to the periodic motion change. The duration of the horizontal phase therefore strongly depends on the duration of the previous motion process. The resistance a motion mode creates for itself increases with its duration and has to exceed the resistance left over by the other motion mode before the change of perceived motion can take place. The difference in resistance which causes the change of motion modes to occur is apparently not large at all, since the phase changes follow each other in brief time intervals, at least if no long lasting motion in one direction has preceded it. If one lets an appropriate pause occur after a longer lasting presentation of the vertical motion (compare above), and then tests

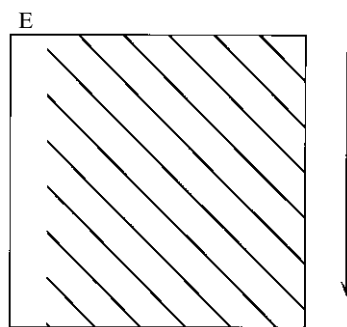


Figure 28. A grating with free line endings visible in the aperture. Objective vertical downward motion is indicated by the arrow. Initially, and for a long time, vertical downward motion is perceived. Two other motion percepts are also possible, however; these are described below in Section IV §12. First, one may see each individual line move horizontally to the left, then vertically down. Second, one may see the line grating pattern moving horizontally, and an illusory surface appearing like a bright white stripe in front of the pattern on the left side of the aperture.

¹⁷ W Köhler *Psychologische Probleme* p. 117 [translation taken from the English version: *Gestalt Psychology* (1947, New York: Liveright Publishing Co.) p. 171].

with the hidden line endings, no extension of the first horizontal phase is observed. The resistance against vertical motion diminished during the pause. It can be assumed that this decay does not exclusively take place during the presentation pause but also during the course of the motion in a different phase. The point in time at which the change between the modes takes place is thus determined by the growth of the resistance against the currently present motion and the rate of decay of the resistance that was created from the previous phase, which would oppose its repeated occurrence.

From this a wealth of questions follow, eg whether the increase in resistance is faster than the decrease or conversely, or whether the decrease during a pause behaves differently than when the motion of the other phase takes place. Further questions are whether the resistance created by a particular motion also hinders motion of the same direction but of opposite sense of motion [eg vertically downwards instead of the (habituated) vertically upwards motion]; and, finally, what degree of 'abstraction' should be allotted to this hypothetical resistance, namely to what extent a resistance created by a particular pattern influences the motion of a different kind of pattern. These questions shall be reserved for a further investigation, which will be concerned specifically with the change of motion. The possibility to induce at any time, as mentioned above, a motion of a particular direction and duration in the process of the free phase change seems to be a powerful method for investigation.

Before we continue with the description of the experiments, we want to introduce, for the sake of simplicity, a change in terminology. Köhler has pointed out the possibility of a close relationship between the course of the figural changes and the spontaneous changes in the processes that Karsten has described as effect of the 'psychic saturation'.¹⁸ We adopt the term 'saturation' and use it quite generally when referring to the cause of spontaneous changes, which occur perceptually over time under constant external conditions; the saturation consists of a continuous change of the internal conditions of the system, which is caused by a long duration of the same form of motion. Hence, 'saturation' is in the following a summary term for the internal causes of the change in motion, the figural changes of the pattern, and the disintegration of the pattern—which have not yet been investigated more closely. We choose the term 'saturation' basing this upon the formal analogy to Karsten's observations, but also guided by the suspicion of fundamental similarities in the processes.

One may assume that saturation takes place also for percepts which are uniquely determined by the stimulus. Only then it cannot lead to a 'reversal' or some other abrupt change in the course, since stimulus conditions do not allow another interpretation. Instead, one then observes color differences becoming flat, feebleness of the figural character, of the impression of motion, and finally disintegration of the form¹⁹ and exchange of motion and rest, eg for pattern motion in an aperture.

§7. *The distinction of horizontal motion*

In the experiment described above, about the change of motion direction, we have to pay attention to the following. During the free phase change, the perception of horizontal motion on average always lasts longer than that of vertical motion. Consider two separate experiments with the same subject: in one case one makes the percept of horizontal motion last for a particular extended time period, with the help of the visible line endings; in the other case vertical motion for the same length of time. Then one finds that vertical is followed by a much longer opposite phase of perceived horizontal motion than horizontal is followed by vertical. The two motion perception modes therefore behave differently with respect to their saturation. Horizontal motion appears to be saturated more slowly than vertical, or the saturation decreases faster.

This is another case of that distinction of horizontal motion, which we encountered earlier (Section III §2). This distinction is not of the horizontal direction relative to the external world but varies with the inclination of the head [ie the retinally horizontal direction]. Strictly speaking, in all its manifestations we are dealing with the distinction of the motion direction in the

¹⁸ Compare K Gottschaldt, 1929 *Psychol. Forsch.* 79, Anm. 1.

¹⁹ See K Gottschaldt, 1929 *Psychol. Forsch.* 79, Anm. 2.

plane of sight.²⁰ Two oblique, alternating motions, like those coming about after rotation of the entire constellation (in arrangement ii), often show corresponding differences in saturation time as well, namely depending on the different amounts of their inclination towards the plane of sight. Even a tiny difference in inclination may have a substantial effect. The motion that forms the smaller angle with the plane of sight is saturated more slowly.

In the experiments on the temporal course of the saturation of pattern motion, this pre-existing difference must be taken into account, since it can be very pronounced for some subjects.

The following experiment clearly demonstrates the distinction of horizontal motion: a line grating pattern moves through a 'parallelogram in a special orientation', whose leading edge is placed vertically. After vertical motion has been perceived for a prolonged time period, horizontal is then seen. In this latter phase the lines do not move along the edge of the aperture. If one employs the same constellation rotated by 90 degrees, such that the leading edges are horizontal, horizontal motion is perceived *continuously*. Probably the saturation for horizontal motion never reaches a sufficiently high level to cause the perceived motion to depart from the aperture-determined direction.

Part 3. The motion of a line grating pattern in apertures of different shapes

[Here Wallach continues to discuss alternations between different perceptual modes that result from prolonged viewing, in cases when the apertures are of different shapes. Some of these aperture shapes can give rise to intriguing percepts which deviate markedly from the underlying physical stimulus.]

§8. *The motion of a line grating pattern in a rectangle*

If one employs a rectangular aperture instead of the square one, then perceived motion in the direction of the longer edges persists for a longer time, before a change in perceived direction occurs. Also, in the further course of the phase change this motion remains temporally favored, the more so the more elongated the shape of the aperture. In a long and narrow aperture only *one* motion direction is perceived, parallel to the longer edges of the aperture.

§9. *The motion of a line grating pattern in a triangle*

In an equilateral triangular aperture, the motion of a line grating is perceived to run from the beginning predominantly in the direction of the aperture edges. Only if the grating is oriented symmetrically within the triangular aperture (figure 29), motion perpendicular to the grating orientation (that is, in the direction of the resultant) is predominant over time. Eventually, however, the intersected edges start to 'lead' the pattern, and the lines are seen as expanding towards the edges. After more prolonged viewing, the motion turns a bit and runs in the direction of one of the edges, and then in the direction of the other edge, and in this manner the perceived motion varies, covering the range allowed by the aperture borders until the scene becomes, with increasing saturation, so unbearable that the subject refuses further observations.

The situation is different when the grating pattern lies obliquely with respect to the triangular aperture (figure 30). Here, motion is first perceived in the direction of that edge whose angle with the lines is closest to a right angle (a), then it turns by 60 degrees and moves along the other edge which is closer to the pattern entrance (b). Finally, after more prolonged viewing the uniform motion of the pattern breaks down. The lines move first along the direction of edge b, then turn and move obliquely upwards along edge c. Frequently in this phase the lines are seen to move in a real arc (dotted line), and this is a motion phase that corresponds to a complete disintegration of the [previously rigid] pattern, since in this phase all lines have different respective motion directions. Soon, however, a remarkably systematic disintegration of the pattern takes place. Then two different motion fields are present in the aperture side by side, one of them moves in the direction of edge b, the other one moves along edge c. The border between the two fields runs at the height of corner A. Here neighboring segments

²⁰ This is the plane defined by the two lines of sight of the eyes.

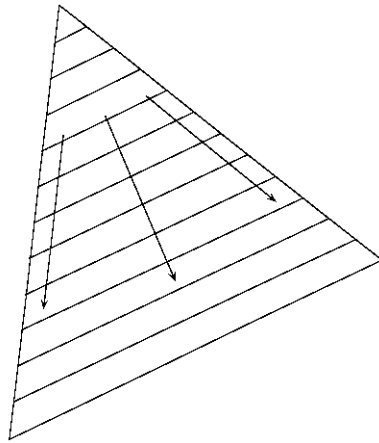


Figure 29. A line grating pattern in a triangular aperture, with the lines parallel to one of the sides of the equilateral triangle. The perceived direction of motion and the scene organization are unstable. First, one sees motion perpendicular to the lines, as indicated by the middle arrow. Afterwards, motion parallel to one or the other of the intersected sides is reported.

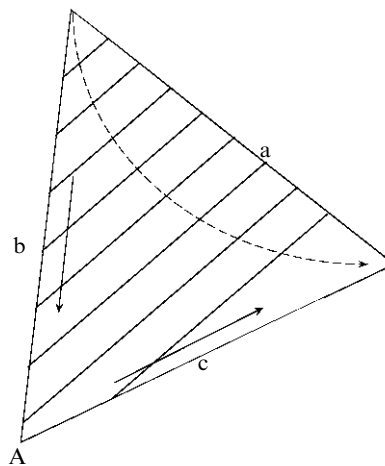


Figure 30. A line grating pattern in a triangular aperture that is oblique with respect to the pattern. In this case all three sides of the triangular aperture are intersected by the line grating. The perceived motion goes first in the direction where the angle of intersection is nearest a right angle such as a, then it turns towards b. Afterwards, pattern motion may disintegrate or it may resolve into two motion fields, one moving parallel to edge b and the other parallel to edge c.

of the line grating pattern have motion directions differing by 120 degrees. One clearly perceives adjacent lines (where one of them has already passed the corner and belongs perceptually to the second part of the pattern, the other one not yet) sliding past each other in opposite directions. This process beautifully demonstrates the complete coupling of motion direction and impression of identity (see Section II §8). Each point along the line, after passing corner A, is perceived to change direction abruptly, move obliquely upwards and exit the aperture at the edge a. In contrast, in the previous mode of perceived motion, the same point was perceived to disappear behind edge c. We further observe that the transition of the single line from one part of the pattern to the other, which takes place continuously at the turning point, is in fact not really perceived; it happens in a concealed manner, not quite accessible to immediate description. The line exists here psychophysically only as a part of the surface it belongs to, and not as an object with its own fate. In contrast, the opposite direction [shearing motion] of spatially adjacent lines that belong to the two different surfaces is very emphatic and conspicuous. One perceives them as sliding against each other as strongly as in cases of objective relative motion. This appearance is indeed contingent on their belonging to differently moving surfaces, which is a perceptual mode that arises as a consequence of the saturation processes. This mode (pattern separation) may persist for a long time. Probably the two almost oppositely oriented motion fields in the same aperture prevent a further increase of saturation, at least as far as the direction of motion is concerned.

We have argued against assuming that in the psychological domain it is self-evident that the perceived direction of motion is determined by the perceptual identity relations (Section II §8). We consider it unacceptable to assume that perceptual identity is primary, and motion direction secondary. Although many people might regard this assumption as 'obvious', it is problematic. In the case of the experiment just described, the inverse clearly takes place: the direction of motion seems to determine the perceptual identity relations. The change in the organization of the objects in the

aperture field (in the sense of field partition and an almost opposite motion of the emerging parts) is apparently a *consequence* of the saturation process affecting the motion direction. On the other hand, there are experiments where the identity of objects must be considered as primary, therefore determining the motion direction. An example is the case when, during passage of a single line through an angular aperture, the perceived motion (normally in the direction of the bisector) can be altered into that parallel to the edge by tracking a line ending (compare Section II §8). In fact, such a distinction is probably of no importance since, functionally, the perceived direction of motion and perceptual identity of parts of the moving object have to be thought of as ‘two sides of the same thing’.

§10. *The motion of a line grating pattern in a curved figure*

A shape as that in figure 31, consisting of two parallel lines and two parallel curved lines, has the tendency to be perceived as bent—say, as a patch of the surface of a cylinder. Gestalt theory would probably give the following explanation: the shape follows the tendency towards ‘good Gestalt’; through the bend into the third dimension a rectangular surface patch of a cylinder emerges, instead of an oblique-angled figure with curved lines.

Almost all subjects can intuitively perceive the right angles that emerge, but in most cases intuition does not suffice to state that the lines b and d (see figure 32) are straight lines projected onto the curved surface of the cylinder. Thus, the subjects may very well ‘know’ that for mathematical reasons it is necessary that the angles are right angles.

With the aid of line motion, we can now demonstrate that the emergent shape bent into the third dimension really possesses the functional properties of a rectangle. To do this, the figure is used as an aperture for a line pattern (figure 32). For the stationary image, the depth interpretation is rendered more difficult by the addition of the diagonal straight lines. The phenomenological sequence is the following. First, one briefly perceives motion perpendicular to the line orientation. It is, however, quickly superseded by horizontal motion, which lasts for a long period, but is frequently interrupted by a motion form corresponding to pattern separation [see below]. The lines move first horizontally along the upper edge and then they follow the curved lateral edge, by executing curved motion independent of each other. At this stage vertically downward motion is hardly ever reported. In order for this to happen, the pattern must be led by the curved edges b and d, and this would imply pattern separation,

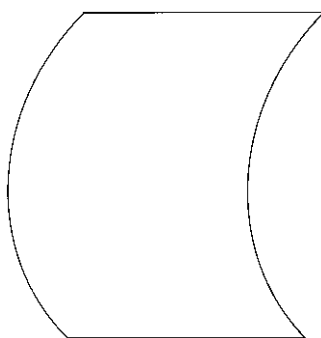


Figure 31. A curved figure that suggests an object in depth, composed of two parallel straight lines and two parallel curves.

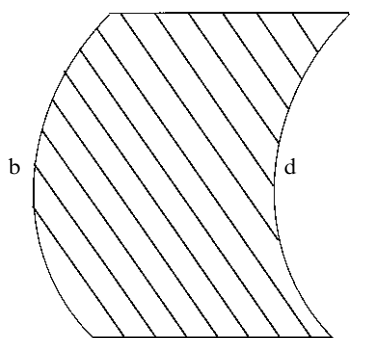


Figure 32. The motion of a line pattern in a curved figure. The three-dimensional perception of the aperture outline affects the perceived motion: after an initial period of perceived motion perpendicular to the line orientation, a vertical direction of motion is reported, and then the aperture appears bent forward in space like a piece of a cylinder.

since each line can follow only individually the curvature, which would prescribe a different direction at each location of the path. Nevertheless, after a while vertical motion takes place. The aperture is seen as clearly bent into space—often to the greatest astonishment of the subjects—and the pattern rotates behind it as a cylindrical surface, as a compact whole, from the top to the bottom. The spatial structures of the aperture and the cylinder are closely matching: they run parallel, and their radii of curvature differ only by the small depth difference between aperture and tape. Under these conditions, the aperture edges b and d are parallel to the pattern, and this is expressed through the coherent motion of the pattern, which moves now without displacement of its parts rigidly from the top to the bottom. This percept, after having occurred once, returns from now on readily and frequently. For the other motion forms, even in the further course of the experiment, spatial [3-D] curvature never occurs, a sign that this curvature only develops if it serves the unification of the motion process. In the cylindrical version, the aperture functions as a rectangle.

§11. *The motion of a line grating pattern in a circle*

In the circular aperture the line grating always is perceived to move perpendicular to its orientation. Here again aperture and grating pattern exist separately only for a brief time period [probably meaning the pattern seems to extend beyond the aperture]. Soon afterwards the grating pattern starts to ‘fit into’ the aperture: the single lines appear to grow and shrink corresponding to the aperture shape, and after a while the perception of translatory motion becomes negligible compared to the perception of expanding and shrinking motion in the orthogonal direction. Then often nothing is left of a rigid pattern: single lines expand and contract. After a while the grating pattern emerges again and moves clearly in the translatory direction, but the perception of motion remains feeble. Only the motion of the line endings at the aperture borders is seen as vigorous; they run at both sides of the aperture in a semicircular path. In the further course of the experiment these modes change imperceptibly into each other, but *a change in perceived direction* for the translatory pattern motion never occurs.

Part 4. Experiments on the motion of line grating patterns: features with an objective direction of motion

[Note: this part still describes percepts that arise during prolonged viewing.]

§12. *Line grating patterns with line endings in the field*

We now return to the experiment in which the line endings of the grating pattern are visible in a square aperture (figure 28, Section IV §4). At first, vertical downward motion is perceived. Then, after prolonged viewing the following mode of motion is seen (for an extended or brief period of time): the lines move horizontally in the portion from the upper right corner to point E, where the line endings enter the field; in the other part of the aperture they move vertically. This is analogous to the change in direction which a single line would follow in an identical constellation (see Section II §1). In this stage of complete pattern segregation, the isolated lines also exhibit the characteristic rebound of the single ‘line with ending’ (see Section III §1). Disintegration of the pattern is not essential to make this nonrigid mode of motion perceptible. Rather, it often occurs that there are two cleanly separated fields that are judged to be different yet exhibit a common motion. They meet each other at point E, and everything proceeds as described in Section IV §9 for pattern segregation in the triangle. In this case, the difference in perceived direction is not as great (only 90 degrees instead of 120 degrees as for the triangle); therefore the motions at the border are not as separated and the motion percept is not as stable. Fixation of the upper edge of the aperture favors this segregated motion. To see a third mode of motion one is advised to fixate the lower edge: rigid *horizontal* motion of the pattern occurs. Where the other two versions of the line endings traveled according to their objective course of motion vertically downwards, a thin strip is now visible. This strip separates, almost like a perceived border, the narrow line-free part of the aperture from the other part.

Behind it, the lines of the patterns disappear “as if behind a curtain”. [Wallach is clearly describing here an illusory contour; see also Section IV §13 and §18.] This holds for objective motion downwards. If the motion runs objectively upwards, then the lines emerge “from behind the surface lying in front”.

This [illusory] border neither necessarily nor immediately emerges with the occurrence of rigid horizontal motion. 9 out of 10 observers perceived these modes of motion but only 7 described the surface in front or anything similar. This developed only when the horizontal motion returned several times. “What’s going on at the left side?”—most of the observers were completely ignorant about that until the new structure had fully developed. Judging by the regularity with which this pattern repeated itself for observers of completely different personalities, we believe that it is not due to a ponderousness of the observers in reporting the appearances, but rather to the really slow development of the structures.²¹ A curious sight is offered by the horizontal motion produced by a tape, on which the line endings that are visible in the aperture are not—as reported above—collinear but arranged in such a way that the pattern has a jagged border. In this case, the ‘curtain’ which emerges during horizontal motion adopts the jagged form and its motion downwards: the lines disappear horizontally behind the occluding surface, which has jagged borders and is moving downwards.

§13. *Grating patterns with interrupted lines*

This spontaneous restructuring is such an interesting process that we investigated further cases in which changes of the figural structure could possibly follow indirectly from the saturation of motion processes. For example, we presented a tape with a pattern of lines which were interrupted in the middle (figure 33). The tape was moved vertically downwards; this vertical motion was therefore mediated by the numerous line endings in the aperture. Nevertheless, after a rather brief period of perceived vertical motion, horizontal motion was perceived. Then a pattern of seemingly noninterrupted lines was moving rightwards, and in front of it—in the middle—there was a stationary vertical white strip. It was very bright, almost glossy, much brighter than the background of the line pattern. When perceived motion reverted back to vertical, the [illusory]

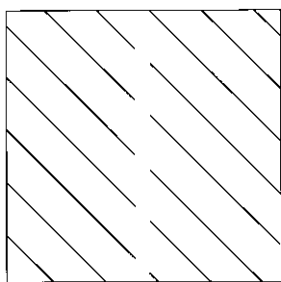


Figure 33. A grating with interrupted lines in a square aperture. The objective direction of motion is vertically downwards. After a brief period of perceived vertical motion, horizontal motion is perceived, and, with it, a stationary (illusory) vertical white stripe is perceived, appearing bright and glossy. When vertical motion returns, the bright white stripe disappears.

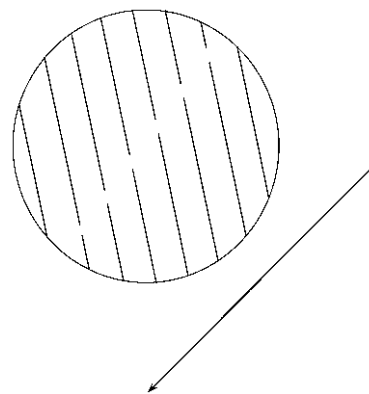


Figure 34. A grating with interrupted lines in a circular aperture. In this constellation, a stationary occluding white stripe is not observed; oblique motion directions either in the objective motion direction (arrow) or perpendicular to the lines are seen, but motion is never seen at a right angle to the objective motion direction as in figure 33.

²¹ About the relationship of this structural reorganization to the restructuring of thought processes we will report in a different framework.

stripe disappeared and the lines again had gaps. It is interesting that there are cases when the integration of the gaps into a unitary stripe failed to appear. In the arrangement of figure 34 no such stripe emerges. The tape is running slightly obliquely behind the circular aperture. At first, the perceived motion is oblique like the objective one. After a while (20–30 seconds) the lines move in a direction orthogonal to their orientation. Then the gaps in the lines are seen as [white] points being displaced along the lines. In the previous case of the square aperture, these gaps lay on a vertical stripe parallel to the edges of the aperture; its occurrence is most likely figurally supported – the ‘white line’ originated as a figurally distinguished form.

If one widens these gaps to, for example, 1 cm, then the slow perceptual development of the above-mentioned structure can be observed clearly. (The arrangement is analogous to figure 33.) In the first brief horizontal phase the gaps dissolve, or the “lines pass behind the gap”, and only in the second horizontal phase “it looks as if the middle is covered with a white strip”.

§14. *Grating patterns with chromatic divided lines*

If one draws the lines of a grating pattern half with black, half with red ink, such that the colors border on each other in the middle, just where in the last experiment the gaps existed (figure 35; red lines are represented by dotted ones), then the color border on the line conveys the objective direction of motion of the tape. Correspondingly, the motion is perceived to run for an extended period of time in the objective direction, which is in our experiment vertically downwards. But then disintegration of the pattern occurs; as far as to the point at which the chromatic border enters the field, the lines are seen to move horizontally, then vertically. Finally coherent horizontal motion is seen. At the same time, the black lines turn red in the course of their passage. This change frequently comes first upon each line individually. The red seems “to enter into the black lines and eat them up”, or the black of the lines “withdraws like a hull and lets the red appear” [sic]. But soon the change of color is perceived as determined by a unified border relating to the whole figure. This border divides the field along the vertical. On the right, the moving lines are black; on the left, after crossing the border, the lines are red. As the culmination of the structural relations one may consider the following version, which developed spontaneously sometimes. In front of the left half of the aperture a queer veil is visible. It is colorless, yet very bright (almost glossy), at the same time completely transparent, and has moreover the property that it makes the black lines moving behind it appear light and red. It relieves

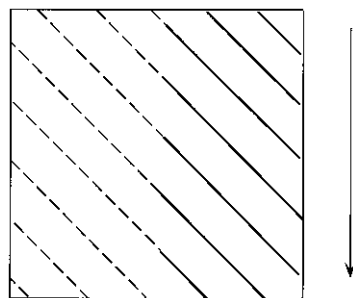


Figure 35. Grating patterns with chromatic divided lines. In this experiment, the lines on the tape are drawn halfway down their length with black ink and the rest of the way with red ink. In the figure, red is indicated by dashed lines and black by continuous lines. The red–black borders are all aligned in the middle of the tape. After a long period of perceived motion in the objective vertical direction, there is disintegration of the motion, and then finally a coherent percept of horizontal motion develops. In this case, a “queer transparent veil” that makes the black lines turn red beneath it is observed on the left side.

the lines of changing their color and makes it possible for them to be uniform in their entire visible extent. During perceived vertical motion no such thing is sensed.

§15. *The crossed-line pattern*

If two line grating patterns of different orientations are drawn on a tape, a crossed-line pattern is formed. If the underlying two line patterns consist of lines of equal but opposite angles of inclination, then a pattern is formed for which the intersections of the lines all lie on straight lines that are parallel to the orientation of the tape, that is parallel to the objective direction of motion (figure 36). This pattern is perceived as a rigid structure of rhombic quadrangles. If the pattern is moved vertically downwards behind a square aperture, this appearance is preserved for an extended period of time. Yet suddenly, sometimes only after several minutes, the picture changes: at first, “for a very brief moment, everything is in disarray”, then the lines are perceived as “sliding horizontally upon each other”. In most cases, this phase is very brief, but it returns again, more and more frequently. It is advisable to insert a break; after it, the horizontal perceived motion may take longer to occur again, but the observer is now capable of a better description. In this phase, nothing is left from the ‘check’ pattern; instead, two separate line patterns are perceived traveling across each other in opposite directions. The lines extending from the upper right corner to the lower left corner slide rightwards, the other ones leftwards, corresponding to the possibilities of their sense of motion. This percept can be conceived as if there are two line grating patterns of different angles of inclination, both of which are seen to move in a manner corresponding to the shape of the aperture. From this perspective two facts are conspicuous:

First, both grating patterns change their phases simultaneously. This can be explained by the fact that the vertical phase implies a common motion of the two patterns; it enables the two grating patterns to enter into a figural bond, to constitute a unified pattern, namely the ‘check pattern’, or any other pattern which is rendered possible through the development of perceptually rigid line crossings. We consider the bond which makes the two patterns cohere in the crossed-line pattern to be very robust, and believe that an extensive saturation of the figural pattern is required at least for the first occurrence of the separated motion.

Second, the perceptual phase of separated horizontal motion is disproportionately brief compared to the vertical one. This remains the case, even if one favors horizontal motion by choosing a wider aperture while keeping the height constant. This could be explained in two ways: the vertical motion constitutes a preferred mode of motion, as mentioned above; the patterns move uniformly and in figural bonding with each other. Or it could be the case that opposite motion of patterns in the same field constitutes a more difficult mode of motion to establish. [In the separated motion mode] the lines

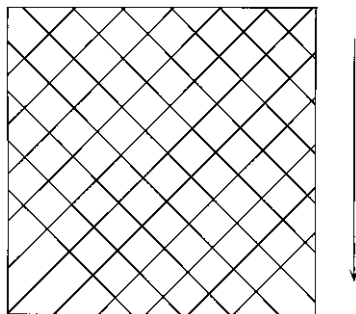


Figure 36. The crossed-line pattern. Two line grating patterns of equal but opposite orientations are drawn on the tape. When the pattern is moved vertically downward behind a square aperture, it is perceived for a long time as a moving rigid structure of rhombic quadrangles. Yet, suddenly, two different line grating patterns are perceived to slide over each other in opposite directions.

are sliding across each other, the motions of the two patterns occur in two different planes, and most of the observers report a considerable difference in depth. Its estimate is 1–4 mm and in most cases it increases with the intensity of the lines of the pattern. The fact that the depth dimension is involved supports the assumption that two translatory motions of extended fields in opposite directions at the same location are physiologically not possible. The lines moving perceptually in front appear sharper and more vivid to most observers. Which lines are in front, and which ones are behind, however, alternates without any regularity in the course of the experiment.

The occurrence of separated motion can be figurally favored by setting off the two line grating patterns against each other by means of different line spacings. Or one can tilt the tape slightly such that the unified [pattern] motion does not run parallel to the edges of the aperture. The same effect can be achieved by letting a right-angled crossed-line pattern pass vertically through a diamond-shaped aperture. During separated motion the lines of the pattern move simultaneously, parallel to the edges of the aperture and perpendicular to their orientation.

If the constellation is such that the motion of the crossed-line patterns runs parallel to the horizontal, then separated motion does not occur. When favored through fixation of the edge at which the check pattern enters the aperture; isolated lines may move in the direction of the separated motion for some moments; however, it never gets so far as to a separated motion of the line gratings. This is another case of horizontal motion being special, which we intend to investigate more carefully.

It is also possible to produce crossing line patterns such that the gratings of lines are tilted to the same side but at different angles. Figure 37 depicts such a pattern. During the perception of horizontal motion both of the groups of lines exhibit the same direction but different speeds (compare to Section I §3). The less tilted lines slide across the steeper ones.

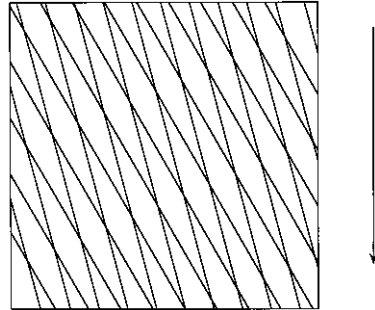


Figure 37. A crossed-line pattern of a second type. It is also possible to make crossing line patterns with gratings of lines that are tilted to the same side of vertical but at different angles. When horizontal motion of such a pattern is perceived, the two separate line gratings are perceived to move in the same half plane but with different velocities. The more nearly horizontal lines slide across the more vertical lines.

During objective horizontal motion, a perception of separate motion does not take place, even when the two crossing line patterns are drawn in different colors, for example, such that they consist of black and red strokes. Perception of vertical motion occurs quite often, but the two line patterns remain solidly bonded to each other; it is as if the pattern, when exposed to the pressure to move vertically, is being bent, but at last it continues to move again in an orderly manner in the horizontal direction.

§16. *The check pattern*

Other patterns can be brought to separation as well, some unexpectedly. All it takes is to move them vertically through a square aperture. For example, we manufactured a tape resembling peasant fabric. In this textile the same number of white and red threads alternate in warp and woof. Therefore, the fabric is striped white–red in two directions. Since the stripes are all equally wide, nothing but checks arise; where white

and white cross, white checks originate; where red warp and red woof cross, red checks are obtained, while red warp and white woof produce the same pink checks as red woof and white warp. The result is a pattern of white, red and twice as many pink checks, with spatial relations as shown in figure 38. The observer describes it exactly as such a check pattern. But it could also be considered as a pattern of crossing pink stripes on a white background, in which the areas of intersection are red. If this pattern is presented [in motion] for an extended period of time in a square or, even better, in a rectangular aperture, as the crossed-line pattern was, then it frequently disintegrates even for those observers who only had seen checks before [at rest]. Then the appearance is changed drastically compared to the percept of the downward moving check pattern. Separated by a considerable distance in depth, two rows of bars move in different directions. The nearer ones are more salient than the ones behind, and all of them are rather uniformly colored. For separated motion, nothing is left of the red checks, which were at the areas of intersection of the pink stripes, except the transparency of the nearer stripes, such that the farther stripes can be seen through the nearer ones. The remarkable appearance of transparency is not observed when crossed-line patterns are used [§15], for which the intersections do not have more intense color as they do here.

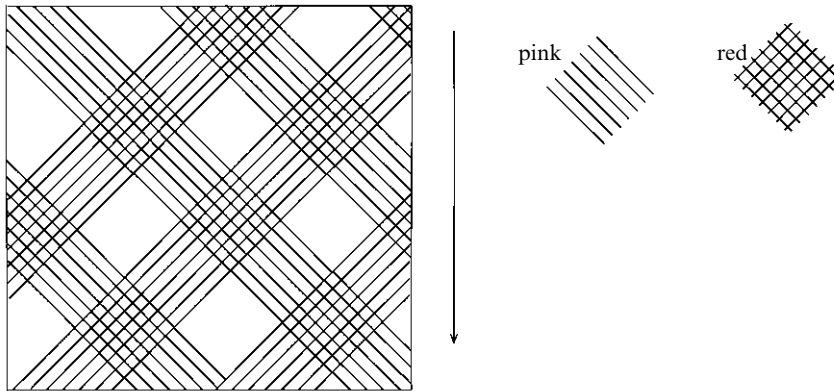


Figure 38. The check pattern. A pattern like a peasant fabric (a gingham check) made of thick red stripes at two opposite orientations is moved vertically behind a square aperture. When the pattern motion disintegrates and horizontal (separated) motion directions are seen, two pink–white patterns appear at different depths, and the one that appears nearer is seen as transparent: the farther stripes are visible through the nearer transparent ones.

§17. *Experiments with patterns made of colored stripes*

To investigate more carefully the color-change processes that occur, we produced a crossed-line pattern consisting of differently colored lines. On a paper tape we drew red ink stripes in one direction, and in the other direction green ones with the same spacing. The strokes had a width of 0.5 cm, and the spacing was 1 cm. Where the ink strokes crossed each other, the complementary colors yielded a grey color mixture. Because of the different colorings of the two line patterns constituting the check pattern, separated motion occurs easily. Those stripes that happened to be moving in front had a deeper color than those in the back and were transparent. Which ones were lying in front and which ones in the back alternated incessantly, irregularly, and slowly. The difference in depth was substantial. Nothing was left from the grey of the line crossings. It obviously had been decomposed into its colored components. The same effect is demonstrated even more strongly when the colored lines are drawn with smaller spacings, such that narrower striped patterns are produced (figure 39). In such a pattern, far more of the grey mixed color than of the red or green is visible initially. Nevertheless, during separated motion, stripes of intense colors without a hint of

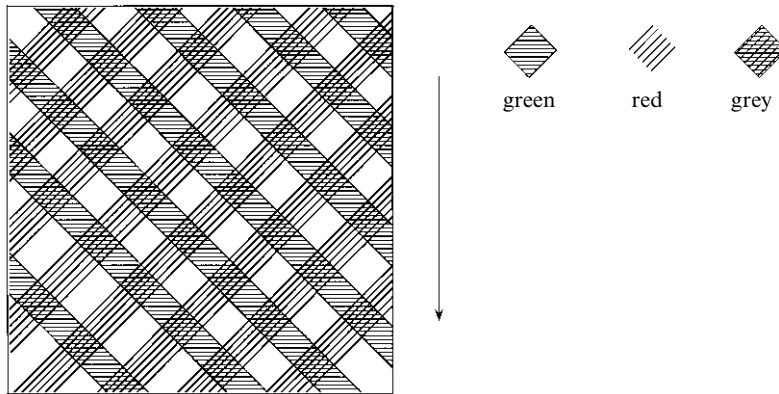


Figure 39. A red and green checker pattern in a square aperture. In the stationary patterns, the regions where the red ink stripes and green ink stripes crossed were seen as grey. When the pattern was moved, the colored stripe patterns separated into two transparent planes, one with red and white stripes, the other with green and white stripes. No grey color regions were seen; instead, observers saw color transparency that accompanied the sliding motion.

greyness are seen. Here, any distribution of the amount of grey on the lines (relative to its area), if it occurred, would necessarily have had a serious effect. This does not happen. The experiment therefore confirms our presumption that in these cases a decomposition of colors occurs. The only essential change accompanying the enlargement of the relative area of the mixed color is a darkening of the stripes that happen to be perceived to move in front. We propose the following explanation: the employed inks are absorption colors. Their light originates in the reflective capacity of the background they are drawn on. As a result, they will look darker with increasingly dense application. Since the differently colored stripes are drawn on top of each other, two layers of colors are present in the areas of intersection and absorb more light. Owing to the large relative area of the mixed color this implies a substantial light reduction of the painted area in its entirety. The observation that this *darkening* goes to the debit of the stripes moving in front is in accord with the experiment with the peasant check pattern, in which even during separated motion the stripes moving in front took over the darker color of the areas of intersection. With a tape made of yellow and blue stripes the experiment comes out correspondingly. Here the intersecting areas are green colored, but nothing of this hue can be seen during separated motion of the stripes; on the other hand, the darkening without a change in hue can again be observed.

Such experiments with narrow spacings between the stripes can easily fail if it so happens that it is not the colored stripes constituting the check pattern that are seen as 'bars' during separated motion, but the spacings, which have a figural character owing to their narrowness, although they are by themselves not homogeneous, but eg red–white or green–white striped. These narrow checked stripes then move on a grey background. Horizontal motion is then only possible—similar to the experiment with the dotted line, Section III §4—through separation of systems. The narrow stripes then move horizontally, while the checks, which they are made of, slide diagonally downwards.

In the experiments described above, mixture colors at the intersections are seen on a white background, and therefore they appear to be primary colors. In the following experiment this is no longer so (figure 40). One grating consists of red and green stripes adjacent to each other; the white of the paper is not visible. At right angles, blue stripes are drawn in wider intervals. Their color is not visible in its purity. With red they yield a violet, with green a sea-green mixed color. There are dark stripes visible at right angles to the red–green pattern, but blue by itself is at first not seen. During separated motion, only two subjects saw blue bars. They slid in front of the red–green pattern which was moving in the opposite direction. After the experiment,

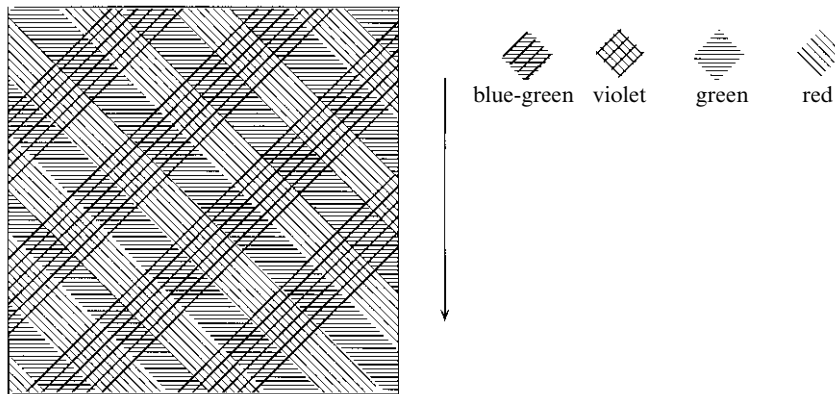


Figure 40. Chromatic stripe patterns without a white background. Here colored ink stripes fill the tape completely: red and green stripes at one orientation and blue stripes at a wider spatial interval in the perpendicular orientation. When moved, the colored patterns separated and moved across each other. Red or green stripes—but not both—were seen to be moving and the other color appeared as a stationary background. Usually, the color of the moving blue stripes was mixed with whichever of the red or green stripes appeared stationary.

these observers confirmed that the perceived blue color of the bar matched the blue of a stroke drawn with the same ink on white paper. However, these were completely isolated cases, and, when the experiment was repeated, even these observers reported the customary version. That is, during horizontal [separated] motion, the two-color pattern does not move as a whole, but sometimes red, sometimes green stripes travel in front of a solid green or solid red background, respectively. These two versions alternate spontaneously, but very slowly. The stripes made of blue ink are violet for the red background, blue-green for the green background, and always homogeneous and saturated. Thus, only the colors of the perceptually moving stripes are decomposed; no decomposition takes place with respect to the coloring of the background.

§18. *The roof-shaped line pattern*

A pattern, like the one depicted in figure 41, consists of two line patterns that meet in the middle of the field. It may be interpreted as a pattern of nested roofs. The vertices are true features which convey the objective direction of motion, which is vertically downwards. Perception of horizontal motion will thus lead to a structural change of the pattern. Usually it only occurs after prolonged presentation. It is preceded not only by vertical motion but also by a version of double pattern segregation: from the two upper corners the lines move horizontally along the upper edge until the vertex emerges and captures them downwards. Finally, when horizontal motion occurs, the aperture is divided by a fine line in the middle, and on both sides of this the line gratings are seen to be moving towards the middle. When taking a closer look, one realizes that the field halves lie in different depth planes. In general, the *right* half of the field is in front, and the lines of the left field disappear behind them as if behind an occluding plane. Therefore, at least one of the line patterns has its ‘curtain’ behind which it can disappear. The right pattern, on the other hand, is immediate and fully visible at one instant, and suddenly “it is no longer present”. Its area emerges from underneath the right edge of the aperture moving towards the left and “is being destroyed at the border (which has been created in the middle)”. The other pattern appears from behind the left edge of the aperture and disappears on the right side behind the surface in front.

Again, the lines running in the frontal plane are also more intense than the other ones. This was reported spontaneously by 8 out of 14 observers. Likewise, 8 out of 14 observers told of yet another percept. During the phase of horizontal, separated motion, the isolated lines of the two patterns no longer meet at the same height, but

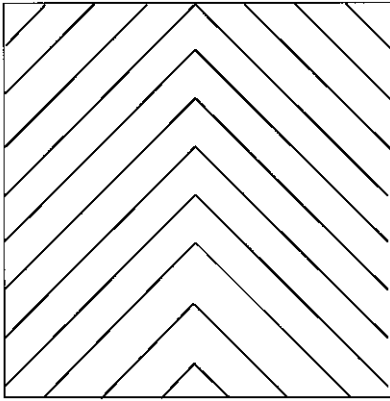


Figure 41. The roof-shaped pattern in a square aperture: perceived motion at first coincides with the objective motion direction.

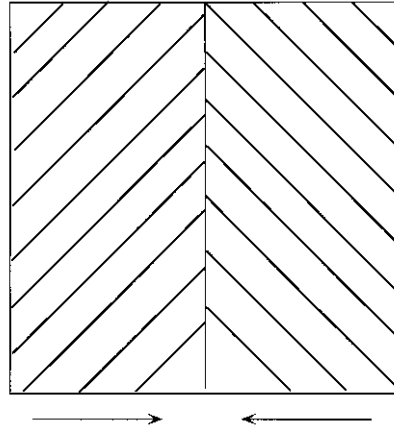


Figure 42. The perception elicited by the roof-shaped pattern (figure 41) after prolonged viewing: the right and left halves of the pattern are seen as separate, with an illusory border ('fine line') between them. The two patterns move horizontally in opposite directions, both towards the center of the field. Most observers report that the right half is closer in depth, as if occluding the left half, and that a shift in the height of the endpoint from right and left is present.

are shifted with respect to each other, as indicated in figure 42. It is as if the segregation into fields of different depths and with different line intensities is accompanied by a temporal delay of the patterns with respect to each other. The shift is such that it can be thought of as if the pattern perceived to be in front is left behind in the objective, vertical direction of motion. This phenomenon requires further investigation.

In the case of the crossed-line pattern, which grating was lying in front alternated. This is not the case in the experiment with the roof-shaped line pattern; a fixed correspondence exists. For 11 out of 14 observers the right field was always in front, for 3 the left one was always in front. These 3 observers were in several respects (which we cannot explain in any more detail here) more 'left-dominant'.

This ratio is not changed when one of the patterns is spatially more extended by moving the screen sideways and the vertices of the roof-shaped lines no longer pass through the middle of the aperture, so that during separated motion the front pattern is narrower than the other one.

Under the assumption that the observers fixate the middle of the aperture, the path of the vertices, the field halves produced during horizontal motion fall onto the retinae of both eyes such that the dividing line of the fields coincides with the vertical meridian of the retina. The right field half, which is imaged onto the left part of the retina, is assigned to the left hemisphere, and vice versa. The functions of this hemisphere are leading for 'right-dominant' individuals. In our experiment, the processes in the left hemisphere are distinguished by the observation that the lines are perceived as more vivid, and the planes are perceived as lying in front. For our 'left-dominant' observers, this is the case in the other half of the visual field, whose processes take place in the right hemisphere.²² A prerequisite for this explanation of the fixed correspondence is, of course, that the direction of gaze is primarily directed towards the middle of the field. Such a direction of gaze is probably maintained by the perceptual process of horizontal motion itself. Suppose gaze is diverted sideways—it will be led back to the middle from both sides of the moving lines.

²² Experiments with a large number of left-handed individuals are not available at this point; therefore we cannot assert that *all* left-handed persons behave similarly in this experiment.

The situation is different for inverse motion of the tape, that is when it is running vertically upwards. The lines are moving during the horizontal [separated] phase sideways away from the middle; therefore the gaze is supposedly frequently diverted sideways, even if the observer is instructed to fixate the middle of the field. The observation of the crucial phenomena is rendered very difficult; in most cases they are nonexistent—a sign that the crucial factor is the direction of the gaze towards the middle of the field.

§19. *The appearance of line endings*

We insert a concluding remark concerning the perception of line endings. This turned out to be the primary motive of all our investigations, since, after all, in most cases a modification in the appearance of the line endings entails a change of the perceived direction of motion²³.

There exist three major appearances corresponding to the ending of lines in a stimulus configuration:

1. The lines end freely in the aperture. This corresponds to motion in the direction of the path covered by the endings.
2. The lines end at an aperture edge. The [perceived] motion is guided by the edge of the aperture.
3. The lines disappear underneath the edge of the aperture and continue to exist hidden behind these. The direction of motion is not limited to being along the aperture edge.

Besides, for the roof-shaped line pattern a fourth appearance occurs during horizontal motion: the lines of the front half of the pattern are abruptly destroyed in the middle. This appearance produces an unsatisfactory impression. It presumably only emerges because of the impossibility of any other manifestation. Manifestations 1 and 2 are not compatible with horizontal motion, and a front edge, as required by manifestation 3, cannot develop for the front half of the pattern.

With respect to the stimulus configuration, two cases exist:

- a. The lines end within the homogeneous field.
- b. The lines end bordering upon the edge of the contour (the aperture boundary).

One might have thought that a unique correspondence exists between the perceptual manifestations and these two principal stimulus constellations. This is not the case; besides the expected combinations a-1 and b-2, the combinations a-3 and b-3²⁴ occur as well. Both for case a and for case b two manifestations come about. On the other hand, *within* the perceptual domain, *unique* rules can be formulated, that is rules that are independent of the stimulus reality:

- I. If (and only if) the direction of motion runs towards the intersected edge, the lines disappear behind it and continue to exist hidden behind it (indifferent to whether the edge is given in the stimulus or exists purely perceptually).
- II. If the line endings as such are visible in the aperture, then the direction of motion follows the path traveled by the endings (indifferent to whether the lines end at the aperture edge or freely within the aperture).

These sentences do not contain any essentially novel truths. We only want to show what kind of simple rules hold *within* the perceptual domain, as opposed to the lack of solid, universally applicable relations between the stimulus constellation and the perception.

The invisible existence of lines beyond the edge of the aperture that we encountered in our experiments is a striking example of the possibility of being ‘immediate’ in the sense of perception, even without a corresponding direct stimulus. As we have seen, the cause for invisible existence has to be sought in the specific course of the stimulus given in the visible domain.

²³ The following considerations are valid for isolated lines as well as line patterns.

²⁴ See Section IV §2 (b-3) and §12, §13 (a-3). The combinations a-3 is missing for isolated lines.

Summary

We investigated the direction of motion of straight lines which were passing through apertures of different shapes.

Objective kinematically, a moving straight line does not possess a direction of motion if it is perfectly homogeneous and without visible endings. Under these conditions, the direction of motion, which a physical object should have, is not represented purely optically. Nevertheless, the line is always perceived as moving in a specific direction, and this direction depends on the figural factors of the stimulus constellation.

There exists a tendency for line motion to be perpendicular to line orientation, and also a tendency to perceive motion along one of the cardinal directions of space. Above all, however, the perceived direction of motion runs as parallel as possible to the direction of the edge of the aperture that the line happens to intersect. If the two aperture edges that are intersected simultaneously have different orientations, then the line pursues an intermediate direction; being a subject of psychophysical 'self-organization', this direction can be derived from the 'Prägnanz' principle.

The changing aspects of the line that the aperture produces when the line passes through it are primarily perceived as changes in the line itself (as expansion and contraction); the line segment visible in the aperture is perceived to be unitary.

Although there are no identifiable features available *in the stimulus* in the case of the straight line, *perceptually* the identity and direction of motion of points on the moving line exist. In this sense, direction of motion and identity are characterized as necessary categories of visual motion processes.

The direction of motion determined by the aperture frequently prevails even though attributes of a physically objective motion (in a different direction) are provided either beside the line or on the line itself.

For a pattern of parallel straight lines a certain resistance against a 'shearing' of the pattern exists, in addition to the characteristic motion tendencies; this has the effect that the pattern moves through the aperture as a whole in a uniform direction, as a solid patch.

If two differently oriented, figurally preferred motions with a uniform direction are possible in an aperture, then they alternate in succession. The cause for this spontaneous, mostly involuntary, change in motion has to be sought in the time course of the motion process: the field is increasingly 'saturated' with the ongoing motion process, and very soon this leads to the formation of the other preferred motion.

If the objective direction of motion as conveyed by features is in opposition to one of the motion directions dictated by the shape of the aperture, then the latter motion will nevertheless tend to prevail when a high degree of saturation in the objective direction is reached. The occurrence of this motion, however, soon causes a structural change of the field, through which the given attributes of the objective motion lose their function, and are re-interpreted in such a way that the field structure is compatible with the perceived direction of motion which runs obliquely to the objective direction. They are re-interpreted such that a 'meaningful' general picture emerges.