Visual bridging of empty gaps in the optic flow

GUNNAR JOHANSSON and ULF AHLSTRÖM
University of Uppsala, Uppsala, Sweden

This is a study of perception of bending motion and jointed rigid motions over large invisible segments of a bending line. In this project, we investigated the visual perception of changing form of lines, built up by a series of dots and presented under highly reduced pictorial conditions. The changing form was indicated by one or two moving and continuously changing visible fragments of the line. The most extreme condition studied was the perception of the bending of an initially vertical 24-dot line, visually represented only by the stationary base dot and the two moving dots at its top. In this experiment, nearly all subjects reported experiencing a smooth bending connection over the 21-dot empty gap. Three experiments are described and analyzed. The results suggest that the human visual system is astonishingly well adapted for derivation of relevant figural information from such severely reduced, continuously changing optical presentation. An explanation in terms of automatic sensory mechanisms related to the physiological receptive field effect is proposed.

In his monograph on event perception (Johansson, 1950), the first author of the present paper experimentally documented that under certain conditions, two dots independently moving on a homogeneous frontal screen were perceived as being connected by an invisible straight linkage (in the following called a *rod*). The dots were experienced as end points of an invisible rod moving in the frontal direction or, sometimes, when the distance between the two dots varied, moving in depth. In 1964, Johansson investigated this perceptual effect further.

These studies resulted in a number of rather provocative experimental findings. They evoked, for example, the hypothesis about the existence of a censorial rigidity constraint (a theoretical position later made use of by Ullman, 1979, as a requirement for a computational specification of visual space perception).

The extensive research on *biological motion perception* (initiated in Johansson, 1973, 1976), which belongs to the same region of problems, has in the last two decades brought about an impressive confirmation of a hierarchical perceptual recording of moving rigid *rods*, indicated only by their moving end points. All these experiments have had in common that they resulted in an immediate and, in nearly all cases, geometrically correct, perception of a person walking, running, dancing, and so forth, elicited by displays consisting of only 12 moving dots. These moving dots represent the joints of the eight main bones of the extremities of a skeleton in motion. They are equally informative about a person's motions in depth as they are about motions in the frontal direction. However, when the person is sitting or standing motionless, a stationary swarm of randomly scattered dots is perceived.

In the 1970s, Johansson proceeded with some preliminary experimental studies on the perception of the continuous bending and straightening of a line under greatly reduced visual information. A vertical line of a constant length, visually represented by seven bright dots along the line (with its base dot stationary) which performed a circular (spiral) bending and straightening (with an approximately constant length during its bending), was shown. The dominating result from these studies was the perception of a smooth circular bending and straightening of the dotted line. However, under similar conditions, the same type of pattern could evoke perception of jointed *rigid* motions. For example, when the number of visible dots was reduced to three dots, two *moving straight lines* connected by a joint were regularly perceived. Each one of these lines was reported as rigidly rotating, with its lowest dot as the center.

Regrettably, this project was never completed or published. However, its astonishing effects were publicly demonstrated on several occasions (e.g., at the Event Perception Conference in New Orleans, 1981). Now the effects found at that time have been actualized as an informative background for our present search for a better understanding of human processing of visual events under reduced optical stimulation. It is also of evident interest that our provisional results have a certain kinship with the neurophysiological studies of receptive field effects (e.g., as studied in monkeys by Hubel & Wiesel, 1968). A recent and, from our point of view, highly interesting, study of a direct relationship between human visual perception of connection over empty gaps on a line and receptive field reactions in *alert* rhesus monkeys to similar patterns was described in two papers by von der Heydt and Peterhans (1989). In these papers, a direct comparison was made between human visual perception of moving anomalous contours (with reference to Kanizsa's, 1979, studies of visual connection over line gaps) and alert rhesus monkey neural receptive field reactions to the same type of

Correspondence concerning this article should be addressed to U. Ahlström, Federal Data Corporation, Science and Engineering Group, 500 Scarborough Drive, Suite 205, Egg Harbor Township, NJ 08201 (e-mail: ulfa@bellatlantic.net).

gaps in moving lines. (In an earlier congress paper, these authors also had referred to Wertheimer's "common fate" effect and to the present senior author's "biological motion" studies mentioned above. The receptive-field effects in *alert* rhesus monkeys studied by von der Heydt and Peterhans [1989] were found to be closely related to these corresponding human perception effects.)

Related Earlier Studies of Perceived Interaction of Moving Dots

Perceptual interaction between a few moving dots was investigated by Börjesson and von Hofsten (1973, 1975), by Börjesson and Ahlström (1993), and by Ahlström (1995). These authors studied such interactions of the motions of such small groups of moving dots in a way related to the rigid motion part of our present problem. Still more directly related are Jansson's (1977) studies of the perception of bending and stretching of a 24-dot line. In Todd (1982), a qualified study of the effects of both straight and bending motion of dotted lines specified by a very great number of dots is described.

Since long ago there have been many studies of visual connections in *stationary* dotted lines. The results from such studies of perception of dotted lines lacking change over time, however, have no relevance in the present event perception context.

EXPERIMENT 1

The senior author's initial experiments on bending lines referred to above, as well as our present pilot studies, seem to indicate that similar patterns of moving dots can bring about a perceptual preference for seeing a *smooth bending* of invisible parts of lines as well as a rigid jointed motion of such phantom lines. Therefore, the main purpose of the present experiments was to clarify the difference in the sensory processing underlying the spontaneous perceptual choice between rigid pendulum motion and a soft bending motion of a dotted line, in both cases specified visually by only a few of their dots.

Method

The construction of the present experiments was founded partly on the earlier studies mentioned and partly also on our experiences from a number of recent pilot studies, mainly with ourselves as observers. The latter studies indicated that it would probably be advantageous to begin our formal investigation by studying the perceptual effects of a single, proportionally very large, empty gap inserted on a dotted line, built up by a rather great number of dots. An additional reason for this choice was that such experiments could have some more or less direct relationship to the receptive-field effects. With these experimental results as a background, Experiment 1 was constructed as follows.

The technical structure of Experiment 1. A straight vertical line built up by 24 points produced by a Pentium PC and displayed on a 17-in. computer screen (MAG DX-17F, 0.26-dot pitch, 72-Hz refresh rate) was chosen as the object for Experiment 1 and also for the next two experiments. Somewhere on this line a series of 12 dots was made invisible, without changing the length or form of the bending line. (Henceforth, such a series of invisible dots will be called a *gap*, and the two visible groups will be called *clusters*.)

Geometrically, this dotted line was bending down on the vertical, frontal screen to an arc of 135° , as can be seen in Figure 1. At this position, the motion stopped for a fraction of a second, and then, with the same speed, the line changed its form backward along the same track until its initial straight and vertical position was attained. After a pause of about 0.7 sec in the vertical position, a new bending and stretching cycle started. With the moments of rest included, this cycle of bending and stretching was completed in about 4.5 sec.

Effects of size of the visual angle of the line under study were expected. Therefore, the display was presented to the subject under three different visual angles of the line length at its vertical position: 3° , 6.5° , and 19° .

Another important question was whether reactions to the position of the *empty gap* on the line would vary with the visual angle size of the line in its vertical position. In order to explore these expected effects, a series of five different such positions was introduced; they were presented in random order to each subject. With the numbering of the dots on the line starting with the stationary base dot as Dot 1, the following five positions of the gap were introduced: Dots 4–15, Dots 6–17, Dots 8–19, Dots 10–21, and Dots 12–23. As mentioned above, henceforth the remaining groups of *visible dots* will be called *clusters*. The position of the last mentioned gap (Dots 12–23) implies that there would be only one dot visible at the top of the line. The result obtained in this condition is of great theoretical interest.

Figure 1. Illustration of the visible parts of the dotted line with the 12-dot gap and with both its vertical and 135° bended position shown.

The display was viewed binocularly. Each subject sat with his/her head in a chinrest with the eyes directed frontally toward the pattern on the screen. During the experiment, the cyclical change of the pattern continued until the subject had described the experienced impression of motion across the gap. The three visual angles were produced by changing the metric size of the display on the screen and/or the distance from the eye to the screen. Figure 1 shows the form of the bending line at its two turning points with its gap on the 8–19 position.

Subjects. Experiment 1 was carried out with 10 subjects. Three of them had experience with this type of experiment (2 of these were the authors). The other subjects were first-semester students lacking such experience.

Instructions. Each subject was instructed to report whether he/she experienced an invisible connection over the gap on the dotted line. If the answer was “yes,” the subject was told that the task was to tell whether for each presentation this connection had the character of a straight line continuously changing its direction, or whether it was experienced as an invisible part of a uniform bending and straightening line.

Results and Preliminary Comments

The results of the experiment are astonishingly clear and uniform. All the subjects reported that they experienced an invisible spatial connection over the empty gap on the dotted line. Thus, our first (and crucial) question got a 100% affirmative answer.

The reports of the perceived connecting line as bending or straight under the different conditions are summarized in Table 1. As will be found in this table, at four of the five positions of the gap on the line, practically all conditions (95%) evoked the report of a bending line connection between the two visible parts of what was experienced as a unitary line (it was like seeing a line in a continuous bending and straightening, the middle part of which was experienced as screened off). For the remaining 5% of the answers, a straight connecting line over the gap was reported.

Table 1
Results From the Five Different Gap Conditions Under the Three Visual Angles Used in Experiment 1

Gap Position	Visual Angle	Percept	
		Bend	Straight
Dots 4–15	19°	10	0
	6.5°	10	0
	3°	8	2
Dots 6–17	19°	10	0
	6.5°	10	0
	3°	9	1
Dots 8–19	19°	10	0
	6.5°	10	0
	3°	10	0
Dots 10–21	19°	10	0
	6.5°	9	1
	3°	8	2
Dots 12–23	19°	0	10
	6.5°	1	9
	3°	2	8

Note—The data show the number of perceived “bending” versus “straight” line connections reported by the 10 observers.

The fifth position, however, where the gap was placed at the top of the line (the 12–23 position with only one dot, Dot 24, visible at the top) evoked a totally domineering recording of a straight connecting line over the gap. Whereas 95% of all answers from Positions 1–4 indicated perception of a unitary circular bending and straightening, 90% of the 30 answers to Condition 5 indicated seeing a straight connection over the gap.

Because Position 5 is special in the respect that only one dot is visible at the top of the line, it is reasonable to assume that the preference for seeing a *straight* connecting line in this condition depends on the lack of any geometrical information about bending at the top of the line (when only a single point is visible). If this assumption should hold true, optical information about a continuously changing direction (at least of the visible top end of the line) would be a critical (and sufficient) requirement for visual perception of bending of the invisible part of the line.

Table 1 also provides a preliminary answer to our question about the role played by the visual angle size of the line. It seems evident that under the conditions of Experiment 1 there is hardly any salient difference in distinctness of information due to the visual angles of the gap (3°, 6.5°, 19°).

EXPERIMENT 2

The distinct grouping of the results of Experiment 1 into a straight line connection and a bending one is of evident interest from a theoretical point of view. One reason is, as already mentioned above, the apparent necessity for at least minimal visual information about bending motion at the top of the line. Another is that the very distinct grouping seems to indicate that the relatively large extension of the gap on the line used in this experiment (half the length of the line) is probably far below a perceptual maximum. Hypothetically, we interpreted these results as (1) indications that proportionally more extensive gaps than those studied in Experiment 1 could be efficiently bridged by the visual system, and (2) indications that at least some liminal visual information about changing the bend at the top part of the line is requisite for the subjects’ perception of continuous bending over the gap.

Method

Experiment 2 was designed to test the relevance of these hypotheses and was thus constructed for the greatest possible increase of the size of the gap on the 24-dot line studied in Experiment 1. It was also planned as a study of the perceptual effect of positioning a single visual end dot either at the top or at the base of the line. Therefore, the stimulus patterns in Experiment 2 were divided in two groups, those for Experiment 2A and those for Experiment 2B.

In Experiment 2A, only the stationary base dot and two, three, or four moving dots at the top of the line were visible on the screen. Figure 2A shows the Experiment 2A condition with only the base

Figure 2A. Only the base dot and the two top dots are visible. The bending line is shown both at its vertical and at its 135° bended position.

dot and two top dots visible. The line is shown at its vertical starting position and at its 135° bent position. This figure is a copy of Figure 1 with all dots except these three made invisible.

Figure 2B illustrates the reversing of the bottom and top roles, giving a pattern with only one visible dot at the top of the line and two or more dots at the bottom end. In this case, however, the maximal number of visible dots at the base part of the line was varied from two to eight dots. This increase in the number of visible dots was applied as a compensation for the less informative bending movement at this part of the line. In the actual experiments, the conditions were mixed and randomly presented to the subjects.

Subjects. The experiment was carried out with 13 subjects. Three of them had earlier experience of this type of experiment (2 were the authors), and the others were 10 first-semester students, lacking such experience. The subject's head position relative to the screen was locked in the same way as in Experiment 1.

Instructions. The instructions given in Experiment 1 were given also in Experiment 2. However, because of the extremely reduced number of visible moving dots in Experiment 2 (two, three, or four moving dots), the subjects were shown a four-dot pattern during the instructions (thus one stationary and three moving dots). They were also told that during the experiment they should pay attention to all visible dots.

Results

The results from Experiment 2A and 2B are summarized in Tables 2A and 2B. Table 2A shows that the re-

Figure 2B. This is the same bending line as that shown in Experiment 2A. However, here eight dots are visible at the bottom part of the line and only one dot is visible at its top.

sults from Experiment 2A are far more uniform than what was expected. Because only a few dots at the ends of the 24-dot line were visible (Dot 1, plus minimally Dot 23 and Dot 24 or maximally Dots 21, 22, 23, and 24), and because the gap therefore cut away most of the line, we had expected corresponding data in Table 1. With two visible dots at the top of the bending line, 32 of the 39 records indicated perception of a bending con-

Table 2A
Results From the Three Different Line Conditions Used in Experiment 2A

Visible Dots	Visual Angle	Percept	
		Bend	Straight
1-23, 24	19°	10	3
	6.5°	10	3
	3°	12	1
1-22, 23, 24	19°	12	1
	6.5°	12	1
	3°	13	0
1-21, 22, 23, 24	19°	13	0
	6.5°	13	0
	3°	13	0

Note—The data show the number of reported “bending” versus “straight line” connections from the 13 observers.

Table 2B
Results From Experiment 2B: The Bending of the 24-Dot Line Is
Visualized by the Stationary Dot 1 and the Moving Dot 24 Together
With a Sequence of One to Seven Visible Moving Dots at the
Base Part of the Line

Visible Dots	Visual Angle	Percept	
		Bend	Straight
1, 2-24	19°	5	8
	6.5°	3	10
	3°	3	10
1, 2, 3-24	19°	5	8
	6.5°	5	8
	3°	6	7
1, 2, 3, 4-24	19°	5	8
	6.5°	7	6
	3°	7	6
1, 2, 3, 4, 5, 6-24	19°	7	6
	6.5°	3	10
	3°	5	8
1, 2, 3, 4, 5, 6, 7, 8-24	19°	7	6
	6.5°	6	7
	3°	4	9

nection over the gap. Three visible dots in this position resulted in 37 bending records, and, finally, 4 dots brought about 100% reports of a bending connection.

The results of Experiment 2B differ drastically from those of Experiment 2A. In Experiment 2A (just as in Experiment 1), hardly any real difference existed between the trained and the totally inexperienced subjects' classifications in bending versus straight line visual connections over the gap. Nearly all the subjects reported under all the three visual angle conditions the experience of a connecting bending line between the end points. In Experiment 2B, the 3 trained subjects reported *straight* line connections at all the three visual angles. However, it was noticed that the task now demanded more concentration from these subjects, as compared with Experiment 2A with its rather self-evident recordings. In contrast to these uniform recordings from the trained group, the results from the 10 first-semester subjects changed between "straight" and "bend" in a seemingly arbitrary way. The data from Experiment 2B are presented in Table 2B.

Comments

Our conclusion from these results is that for the trained observers, there existed in the Experiment 2B patterns visual information sufficient for distinguishing between bending and straight lines, but that this information was far less than that for the bridging of the 50% gap studied in Experiment 1. Therefore, a number of the observers who lacked earlier experience from such tasks evidently reacted in the Experiment 2B situation in a rather ambiguous way.

EXPERIMENT 3

Geometrically, the type of bending studied in Experiments 1 and 2 is rather simple. The results of these ex-

periments indicate that, at least for this type of bending, the relative motions between the two or more dots at the top end of the line (with a stationary bottom dot) determined the shape of perceived bending. Furthermore, in Experiment 2A, these three dots provided high-quality information about the invisible bending and straight parts of the line between the bottom dot and the cluster for nearly all subjects. Given these findings, we found it appropriate to proceed with a study of the perceptual reaction to reduced optical information from a more complicated type of bending of a dotted line.

Results from pilot studies indicated that a dotted, continuously changing sine curve was probably an appropriate object for such a study. Furthermore, these studies had indicated that for such a complicated type of bending of a dotted line as well, it was possible to apply the principle from Experiment 2A concerning reduction of the number of visible dots to an absolute minimum.

Method

The sine curve was constructed as moving horizontally from right to left in an endless manner, as if seen simultaneously through two very narrow vertical windows. Thus, on the screen only two clusters were seen, cut out from the moving sine curve and moving vertically up and down, often in different directions and with individually varying speeds. In Experiment 3, the two clusters always had the same number of dots: two or four. The number of *invisible* dots along the sinusoidal line separating the clusters specified the size of the empty gap. As small fractions of a moving sine curve, the clusters continuously changed distance and/or direction of motion relative to each other. The same held true for the spatial relations between the dots in each cluster. Figure 3 shows a cycle of the sine curve with the two visible 12°, two-dot clusters, but with the invisible dots along the curve made visible by pixel-size dots.

Design. Experiment 3 was planned so that its results would be comparable with those of Experiments 1 and 2. Therefore, in Experiment 3 we also investigated possible effects of the size of visual angle; two sizes of vertical visual angles between the turning points were introduced, one 12° and the other 3°. In each of these two conditions, two clusters with a numerically constant empty gap between them were exposed as described above. The number of dots in each cluster was two, three, or four. Possible effects of size of the empty gap between the two clusters (in number of invisible dots along the sine curve) were studied.

In the 12° conditions, the gap was extended over either 8 or 12 dot positions (see Table 3), and in the 3° condition, it comprised either 2 or 3 positions (thus a ratio of 2:3 in both conditions).

Irrespective of the size of the gap between the clusters on the continuously changing sine curve at the 360° cycle, there were two phases of excessive bending (at the top and bottom part of the sine curve), and between them, two phases with indications about sloping and, for a moment, approximately straight lines.

Subjects. Ten 1st-year students took part in the experiment. None had taken part in the earlier experiments. The subject was positioned relative to the pattern on the screen as in Experiments 1 and 2.

Instructions. At the start of each session, the subject was given both printed and oral instruction. To make the subject familiar with the stimulus pattern, a running 6°, two-dot plus two-dot version of the actual pattern (not used in the experiment) was shown. After the subject had been looking at the two moving clusters for a while, he/she was asked whether the two moving groups of dots were perceived as moving independently of each other or whether an invis-

Figure 3. A cycle of the sine curve with its two visible two-dot clusters and with the invisible dots represented by pixels.

ible connection between them was experienced. All 10 subjects answered that they clearly perceived an invisible connection. Thus, our first and crucial question got a 100% affirmative answer.

After this test, the subject was told that a number of different types of such patterns would be shown and that his/her task was to report moments when the invisible connection between the two clusters was experienced as approximately *straight* and when it was *bending*. This had to be done by immediately saying the Swedish terms for "straight" and "bend" (in Swedish the shorter *rak* and *böj*), respectively. The subject was also told that he/she must give this report immediately at the moment at which the character of the experienced connection was evident. Furthermore, each subject was instructed to promptly report whether, at any time, the impression of connection between the two clusters was lacking.

Results

The experimental design included eight different conditions. We found it advantageous to choose the two different sizes of double the amplitude of the sine wave in visual angle as a basic classification. Thus, the results will be specified in two groups with respect to the size of visual angle (12° and 3°), with four different conditions for each of them. Each condition was iterated in random order until it had been shown five times.

12° visual angle conditions. These results are presented in Table 3A. As the table shows, there was just a liminal difference in the quality of the records for the 8-dot gap and the 12-dot gap. The only difference in number of correct records was that for one of the two 12-dot patterns, 8 subjects, as opposed to 9 subjects in all other conditions, reacted with a correct response. Thus, the visual system seems not to be more than in a liminal way sensitive to the different sizes of the gap studied here. The same holds true for the different sizes of the clusters. For most conditions, the subjects' reactions to the moving and changing clusters have resulted in a distinct and geo-

metrically correct percept of the bending and straight phases of the changing sine curve. Thirty-five of the 40 records were geometrically correct. (One subject has reported "no connection over the gap" in three of the four conditions, 2 other subjects reacted in the same way at one of these conditions. Three of these "no connection" reports were given at the 12-dot gap condition and the other two at the 8-dot gap condition.)

Another subject in this group reacted in a different way, only at the 4-dot cluster, 12-dot gap. He said that it

Table 3A
Results From the 12° Visual Angle Conditions: The Number of the 10 Subjects in the Group Who, With Five Iterations, Correctly Identified the Bending and Straight Phases at All Four Conditions and the Subjects Who at Some Conditions Did Not Experience a Functional Connection Between the Moving Clusters

Cluster Size (No. Dots)	Gap Size (No. Dots)	Correct Records (No. Subjects)	No Interaction (Subject No.)
2	8	9	5
2	12	9	6
4	8	9	5
4	12	8	5 and 9

Table 3B
Results From the Sine Curve, 3° Visual Angle Conditions: Number of the 10 Subjects in the Group Who, With Five Iterations in the Actual Conditions, Correctly Identified the Bending and Straight Phases

Cluster Size (No. Dots)	Gap Size (No. Dots)	Correct Records (No. Subjects)	Always Bend (No. Subjects)
2	2	9	1
2	3	10	0
3	2	6	4
3	3	7	3

Note—Reactions of the subjects who in some conditions did not record the straight moments are specified in column 4.

was easy to perceive the connection as straight (and jointed) there but hardly possible to see it as bending.

These six deviating records are of interest from both a technical and a theoretical point of view. Five of the subjects in this group did not mix up "straight" and "bend." Their records instead say that in these cases, the moments of straight connections over the gap were not recorded. Three of these reports were given by the same subject and the other two by 2 other subjects, each one reacting in this way only once. These results indicate that in this group of subjects, there was a small variation in the ability to record a geometrically correct interaction over the gap. This observation makes it logical to suppose that in our experimental situation, the 12° visual angle distance between the top and bottom of the sine curve might have been rather close to the limit for a spontaneous recording of interaction over the empty gap. In a few cases, it might also have been due to a disturbing effect of pursuit eye movements. However that might be, trained observers looking at this pattern have experienced an unusually strong bending connection just at these turning moments with the two clusters moving in opposite directions.

3° visual angle conditions. These results are summarized in Table 3B. In this part of the experiment, all subjects reported that they experienced a bridging over the gap in all conditions. Sometimes, however, some of them did not react to the "straight" moments.

As the table shows, in the 2-dot cluster condition, 9 of the 10 subjects reported "bend" and "straight" at the correct moments. The deviating subject reported "bend" over the whole cycle. The 3-dot clusters yielded quite different results. A number of subjects (like the single subject in the 2-dot cluster condition) continuously reported "bend" during the whole cycle of the sinusoidally changing form.

Expanding the two clusters with one dot each meant shortening the duration of the straight phase. It was possible that this straight-line phase was too short for some subjects and therefore brought about the perception of bending over the whole cycle. If so, these subjects correctly reported *their* percepts.

To evaluate this possibility, a post hoc study of the reaction of an experienced observer (the senior author) was carried out. This observer clearly perceived both the bending and the straight moments but also found that in the 3-dot cluster conditions the straight moment was very short. These observations support the preceding hypothesis.

THEORETICAL OUTLOOK

This project was focused on a search for characteristics in changing stimulus patterns which from reduced optical information can evoke geometrically passable percepts of the bending of a line or the rotation of jointed straight lines.

In Experiments 1 and 2, we investigated the visual perception of such reduced optical information for the spiral bending of a line with a constant length. With a similar reduction of visual information, in Experiment 3, we studied the visual capacity of correct perception of the bending and straightening phases of a moving sine curve with its continuous change of distance, direction, and speed between the dots along the curve.

Two changing fragments of this curve (clusters) were presented as if seen through two stationary, extremely narrow vertical windows, separated by a constant number of invisible dot positions (see Figure 3).

As a basis for our analyses, we will make use of two previously established perceptual effects: (1) the perceptual interaction between series of moving dots separated by empty gaps, as studied especially in biological motion research, and (2) the classical *present-time* perceptual memory function. The first of these effects, from biological motion research, we have described at the be-

Figure 4. The figure illustrates the geometry of the bending process in Experiment 2A with its stepwise change of position of the moving 24 dots. (See text.)

ginning of this paper. A reminder regarding the present-time function might be useful, however.

The Short-Time Preserving of Visual Information Changing Over Time

The visual sense, like the other senses, works with a short-time memory saving of the momentary sensory information, a saving with a usually assumed durability of about 5–12 sec. This memory function was studied especially in Germany during the last part of the 19th and the first part of the 20th centuries and was, after William Stern in German, called *Präsenzzeit* (“present time”; see, e.g., Fröbes, 1923, pp. 124ff, and Woodworth & Marquis, 1947, pp. 564–565).

In Johansson (1979), such a perceptual short-time function was declared a necessary memory component of visual event perception. This sensory short-time event recording is indispensable for both animals and people. Without storing for a few seconds the visual recording of optical changes over time, the human perception of, for example, a flying bird or a walking person would not be possible, and the same holds true for auditory recording of, for example, a melody or a human speech. In the same way, frogs would not be able to capture flying insects, and an owl could not catch a running mouse. Such continuous short-time perceptual recording of continuity in the ongoing change over time of sensorial stimulation is a prerequisite for survival in all species of animals, including the most primitive.

In our search for a relevant explanation of the perceptual reactions, in the present project, this short-time perceptual memory process was accepted as a vital perceptual function. Together with the strong perceptual predisposition to fill up empty gaps in visual stimulus patterns, short-term perceptual memory makes it possible that the motions and the changing form of the visible parts of the dotted lines in our study were recorded as belonging to the same perceptual unit.

A Geometrical Event Perception Model Relevant to the Three Experiments

With an anchorage in earlier research on visual perception of rigid rotary motion evoked from perceptual interaction between moving dots, we will propose a geometrical interpretation of the perceptual effects, found in the three experiments described above—an interpretation valid for both the rigid and the bending motions studied here.

The extensive research on biological motion, with its hierarchical system of rigid, jointed motions and its immediate and definite percepts, has afforded important material. The theoretical basis for these effects, first described in Johansson (1973, 1976), was founded on earlier studies of event perception also done by Johansson (1950, 1964). Already in these two initial papers, the senior author pointed out that visual presentation for a fraction of a second of the 12 moving dots representing the main joints of the arms and legs of a walking person

was enough for a subject’s visual recording of human walking.

Since Johansson’s (1973) initial work, biological motion has been investigated further in a number of studies by Cutting and his co-workers. As a very special example of such studies, we will mention Cutting (1982), in which corresponding visual effects of a few moving dots representing extremely simplified trees and bushes moving in the wind were analyzed. There are by now many such studies of complicated interactions of rotating rigid lines, indicated only by their moving end dots. To our knowledge, however, studies of corresponding soft bending of lines in such biological motion patterns (e.g., by moving snakes, worms, insect larvae, etc.) have never been published.

We will begin our interpretation of the present experimental results by specifying what were found to be relevant geometrical characteristics of the changing stimulus patterns when the present-time effect was taken into consideration. Partly because of its extremely reduced and simplified visual information, the pattern in Experiment 2 was found to be most useful for the construction of a general model applicable in valid geometrical interpretations of the results of the three experiments. Thus, Experiment 2 was chosen as the basic object for our analysis.

Figure 4 depicts the 24-dot line with a visible 2-dot cluster pattern bending 135° relative to its initial straight vertical position. In order to specify the geometrical process underlying the motion of the visible dots in Experiment 2A (and in Experiment 1), the moving *not visible* dots in the system also are shown in this figure. The three visible dots are indicated by diamond-shaped signs and all the “invisible” but geometrically active ones by pixel-size dots. Consequently, the figure contains all the existing *geometrical* specifications about the changing spatial relations between the moving dots.

As will be found in the figure, the successive bending of the line is similar to a frontal bending of an elastic vertical steel wire. The bending of the initially vertical, straight line was produced by a successive adding along the line of a diminutive (nearly 12′) change of the angle between each dot and the next one along the series from the base dot to the last one (Dot 24) at the top of the line.

After the first series of successive changes of direction along the line from its stationary bottom dot to its top dot, the direction of a hypothetical line between Dot 23 and Dot 24 has changed 4.5° from its initial vertical position. Thus (as can be found in the figure by counting the number of iterations of the line bendings), with this bending process iterated 20 times, the hypothetical connection introduced between the two top dots has changed its direction 90° and gotten a *horizontal* direction. Consequently, after 30 iterations of the top bending process, it has reached its 135° end position. This geometrical process of change from a straight line to the maximally bended one of about the same length was in the experiment performed in about 2 sec. After a break of about

0.3 sec at the 135° turning point, the return along the same track and with the same speed began. At the return to the vertical position, there was a stationary moment of about 0.7 sec before the next bending/straightening cycle commenced. These sequences of bending/straightening continued until the subject had described his/her percept.

Theoretically, this process implies that a subject initially perceives the three dots as components in a vertical line. Then, with his/her attention concentrated on the changing top dots (and simultaneously peripherally recording their changing relation to the stationary base dot), the subject, as a consequence of the “present-time” visual memory effect, will be continuously perceiving and *conserving* (1) the complete changing (bending and/or straightening) curvature of the track of the cluster as a unit, connected to the stationary base dot, and (2) the continuously changing direction of linear connection (connections) between the two or more dots inside the cluster. Thus, if we take into consideration these short-term memory effects, it seems evident from these effects that the subject was, while looking at the moving dots, continuously informed about the changing curved form of the motion track of the cluster relative to the stationary dot and also to the coordinated miniline change of direction between the cluster dots.

Geometrical Characteristics Evoking the Perception of Bending

Thus far, we have only touched on the basic theoretical possibilities of finding the active mechanisms underlying visual recording of bending over empty gaps. We will continue with a description of the results of our search for distinct features in the changing geometrical structure of the Experiment 2A display, underlying the wide visual angle results specified in Figure 2A.

Hypothetically, the changing form relative to the base dot of the curve, drawn by the moving cluster as a unit, could be such a feature. However, the results from Experiment 2B had shown that when Dot 23 was made invisible and thus only one dot was visible at the top of the line while the base cluster showed a number of visible dots clearly specifying the bending motion, the subjects' results changed in a dramatic way. Instead of the nearly exclusive perception of a bending over the gap, received from Experiment 2A, a dominating perception of a rotating *straight* line, connecting the highest number of visible base cluster dots (varying from Dot 2 to Dot 8) and the single visible top dot appeared. This indicates that the visible curved form of the dotted line at its base end does not, even when indicated by up to one third of the number of the moving dots, carry sufficient information about bending over the gap. The presence of two or more visible miniline-connected moving dots at the *top* of the bending line seems to have been the decisive condition for the perception of bending in Experiment 2A and also in Experiment 1. When such inside-cluster information was lacking, the subjects in a majority of the

conditions reported the perception of an extended straight-line connection between the last visible dot at the bending base end of the line and its single top dot. This tells us that the visual system in this situation primarily reacts with a distinct linear connection between the last base cluster dot and Dot 24. As will be found in Table 2B, this holds true for the 3° and 6.5° visual angle sizes as well as for the 19° visual angle. Thus, also in this experiment, the visual angle size of the gap to be bridged played no deciding role. Consequently, another (or an additional) geometrical indication for perception of bending had to be sought for.

The regularly changing spatial direction of a presumed connection between the two (or more) visible cluster dots at the top of the line during its bending/straightening phases was found to entail the needed information. At the start of the bending cycle, the invisible connection between the dots in the top cluster has an exactly vertical direction (we will in the following use the term *minilines* for these not drawn but still perceptually recorded connections between neighboring dots). By counting in Figure 4 the number of cycles of steps of changing direction along the line of the neighboring dots, the reader will find that after 20 additive cycles of such change of direction between neighboring dots, the hypothetical miniline between the two top dots has successively changed from the initial vertical position to a distinct *horizontal* direction. Thus, owing to the ongoing bending of the 24-dot line, the miniline between Dot 23 and Dot 24 has rotated 90° relative to its initial vertical position. Consequently, after 30 iterations, it has rotated 135° and thus reached its turning point. This can easily be seen in the figure.

These results are consequences of the construction of the changing pattern and the chosen liminal angle of the gradual rotation common to all the minilines. They indicate that a one-cycle angular change along the line between the neighboring dots brings about 4.5° of change of direction of the miniline at the top end of the line. This indicates that the changing direction of the perceptually recorded miniline between the two top dots was a crucial factor for the visual recording of bending over the gap. It *explains* why more than one visible dot at the top of the line was required for visual recording of bending under our experimental conditions, and it determines the degree of the geometrically stepwise rotation of the minilines.

Geometrical Characteristics Evoking Perception of Jointed Rigid Motion in Experiments 1 and 2

Contrasting with the subjects in Experiment 2A, the majority of the subjects in Experiment 2B revealed an evident degree of uncertainty in their choice between bending- and straight-line connections. This uncertainty, however, was found only in the reactions from the 10 inexperienced subjects. The 3 experienced subjects, without much hesitation, reported perceiving a straight-line connection in all the Experiment 2B conditions.

As has already been observed, these straight-line recordings have a direct relationship to the structurally deviating Condition 5 in Experiment 1 with only one dot visible at the top of the line. Table 1 shows that this condition resulted in 27 straight-line percepts and only 3 bend percepts, whereas the four other conditions (all with two or more visible top dots) together resulted in 114 "bend" and 6 "straight" records. These results, from the 19°, 6.5°, and, 3° visual angle conditions, indicate a nearly complete distinction of perception of "bend" and "straight" connections over the gap. Possibly the striking difference between newcomers and experienced subjects in Experiment 2B could to a certain extent be a consequence of the extremely reduced information in the pattern under study in comparison with the corresponding Experiment 1 pattern.

We conclude, however, that under our experimental conditions in Experiment 1 and Experiment 2, the visual system reacts in a similar way to wide angle gaps and to gaps limited to central vision; that a single visible dot at the top of the bending line under study normally yields perception of a straight connecting line over the gap; and that two or more dots at the top of the bending line will evoke perception of a soft bending.

These findings were of great significance in our search for geometrically effective sources of the shift from visual perception of soft bending of the line to perception of a rotating straight-line connection of the softly bending base cluster and the single moving top dot. As mentioned above, such reactions to impoverished visual information exist in primitive animals also. This implies that the spontaneous distinguishing between straightness and bending under the extremely impoverished stimulus conditions found in our experiments must be regarded as an inheritance from early phases of the evolution of vision.

INTERPRETATION OF THE RESULTS OF EXPERIMENTS 1 AND 3

Rotation of Minilines as Information About Bending in Experiment 1

In Experiment 1, the effects of 12 moving dots, divided into two clusters and separated by 12 invisible dots, were studied. Technically, the bending process of the 24-dot line was exactly the same as in Experiment 2A. Only the numbers and positions of visible dots differed, and they differed very much. In Experiment 1, there were two groups of moving visible dots, and in Experiment 2, there was only one such group together with a single stationary dot at the base of the line. Whereas in Experiment 1 the total number of visible moving dots was 12, it was 2, 3, or 4 in Experiment 2A. However, because the geometrical structure of the bending process as such in the two experiments was the same, the miniline specification of the bending process is valid in the analysis of the geometry of bending in Experiment 1 as well as in Experiment 2. The main difference is that the

number of dots in the Experiment 1 visible clusters at both ends of the line caused these clusters to have perceptually the characteristic of flexibly jointed minilines like links in a chain.

Consequently, application of the jointed minilines model as a means of comparing the geometrical structures in the two experiments shows that, geometrically, in Experiment 1 far more jointed rigid miniline information about bending was available. The result, however, was that, in Experiment 2A, only 9 of the 117 accepted descriptions given by the subjects belonged to the category "straight." It is also critical that, with one exception, more than one dot was visible at *both* ends of the dotted line in Experiment 1 and that the gap was far less extensive than the Experiment 2 gaps. Therefore, our preliminary conclusion beforehand had been that in Experiment 1 there would be, geometrically, a considerable redundancy of visual information about bending, a redundancy lacking in Experiment 2A, and that this would be shown in the results. Yet, as will be found when one compares the results of these two experiments, this difference had little or no effect.

Information About Bending in Experiment 3

The geometry of the patterns in Experiment 3 differs very much from that of the Experiment 2 and Experiment 1 patterns. Here the stimulus pattern consisted of two changing and vertically moving clusters with constant horizontal positions, cut out from a horizontally moving sine curve. Therefore, pictorially the clusters were moving vertically up and down on the screen, often in opposite directions. The direction of the perceptually recorded minilines between the dots in the clusters varied during most of the cycle. (See Experiment 3, Method section, above.)

In one essential respect, the changing Experiment 3 pattern was closely related to the patterns in the two other experiments. The visual information was received from two clusters of moving visible dots, and the systematically changing direction over time of the minilines in these clusters stood out as a parallel to the informative mechanics in the other two experiments. In Experiment 3, the stimulus pattern represented a line, continuously changing its form on a frontoparallel plane. Thus, generally, the same type of geometrical and perceptual specifications as those developed in the description of the construction of Experiment 2 could be applied here.

To get an empirical verification of the preceding conclusions, a pilot study of the Experiment 3 pattern with only one dot in each "cluster" was arranged with the senior author as observer. The result was quite convincing: The two dots were now seen as moving vertically up and down in different phase and they were rather unavoidably experienced as the end points of a connected, continuously moving straight line. Thus, this condition had no perceptual relation to the two-dot and four-dot conditions. Instead it evoked the same type of perceptual reac-

tion as did the one-top-dot conditions in Experiments 1 and 2B.

Theoretically, these principles for the analysis of bending of lines under reduced information are applicable not only to any kind of changing form of such lines with a frontoparallel orientation, but also, after the addition of a supplementary specification of the motion in depth to be studied, when the lines are bending or rotating in any direction in 3-D space.

As has already been pointed out, geometrically the Experiment 3 type of change of the form of a line was far more complicated than the one studied in the two other experiments. Therefore, it was expected beforehand that particularly the motions of the clusters in opposite directions at the two turning parts of the sine curve would be disturbing for the subjects' recording of a curved connection over the gap. Contrary to this expectation, we ourselves found that these moments of experienced drastic change of direction of the line stood out as distinct and highly informative. And all the subjects correctly reported *böj* ("bend") at these two phases of the bending cycle.

CONCLUSION

Effects of Size of Visual Angle of the Empty Gap Studied in the Experiments

In the planning of this project, perceptual reactions due to the visual angle size of the empty gap under study were expected to be of considerable theoretical interest. Therefore, in each of the three experiments, such variations of the gap size were introduced. However, contrary to our expectations, the results indicate that under our experimental conditions, limited to frontoparallel presentation of the changing clusters, there was no established difference in the subjects' reactions to 19°, 6.5°, and 3° size of such empty gaps. These results indicate that human vision is well adapted for efficiently bridging over both small-angle and wide-angle invisible sections on a moving line.

Final Remarks

The main purpose of our project was to identify and explain spontaneous sensory reactions to some highly reduced and continuously changing visual stimulus patterns, patterns nevertheless immediately evoking adequate spatial information and, in real-life situations, sometimes instantly eliciting risk-avoiding muscular reactions in human beings and animals.

From a wide, biological point of view, the seemingly rather strange visual capacity studied here stands out as

being of a vital significance in the process of evolution. Therefore, we have called attention to recent neurophysiological research on a similar kind of sensory processing in *alert* rhesus monkeys, a research with both problems and results functionally related to those reported here.

Our project has resulted in some illuminating findings to our knowledge not earlier observed in research on visual perception of lines. We hope to be able to proceed with further studies in this field.

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