Visual perception of motion in depth: Application of a vector model to three-dot motion patterns*

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The aim of the present study was to identify spatial properties of three-dot motion patterns yielding perceived motion in depth. A proposed vector model analyzed each pattern in terms of common and relative motion components of the moving parts. The dots moved in straight paths in a frontoparallel plane. The Ss reported verbally what they perceived. The common motion did not affect the kind of perceived event (translation or rotation in depth). Relative motions toward or away from a common point, i.e., concurrent motions, yielded perceived translatory motion in depth. Parallel relative motions toward or away from a common line generally yielded perceived rotation in depth. Complex motion patterns, consisting of concurrent and parallel relative motion components combined, evoked simultaneously perceived translation and rotation in depth under certain phase conditions of the components. Some limitations of the model were discussed and suggestions made to widen its generality.

Several studies concerned with perceived frontoparallel motion have concluded that the visual system extracts the motion vector that is common to the moving parts (Wertheimer, 1923; Duncker, 1929; Johansson, 1950).

The analysis of motion into vector components has been further elaborated by Johansson (1964, 1971) to cover perceived motion in depth. Parallel motions in depth are represented on a picture plane by motion vectors toward or away from a common point, with proportionally equal velocity relative to this point. These motion vectors are called concurrent motions. Johansson (1964, 1971) concluded that the visual system extracts concurrent motions yielding perceived translatory motion in depth.

In a recent study (Börjesson & von Hofsten, 1972), a vector model similar to that of Johansson's (1964) was developed in order to isolate relevant concepts for prediction of perceived motion in depth of two-dot motion patterns. Although it was concluded that the model was a successful tool for identifying determinants of depth perception, its range of application is limited to two-dot patterns.

Any two-dot motion pattern can be considered as the projection of two fixed points on a rigid *line* moving in space. Any three-dot motion pattern can be considered as the projection of three fixed points on a *plane* moving in space. Since everyday perception involves perceived surfaces as well as perceived edges, an application of the

model to three-dot motion patterns would widen its scope of validity.

The general aim of the present study was to lay down spatial determinants for depth perception in three-dot motion patterns by applying the vector model proposed by Börjesson and von Hofsten (1972).

APPLICATION OF THE VECTOR MODEL TO THREE-DOT MOTION PATTERNS

Each individual motion within a motion pattern will be divided into a *common* motion vector and a *relative* motion vector. The common motion vector has the same magnitude and direction for all individual motions. Relative motion vectors are defined as a set of motion vectors, the sum of which equals zero. For any three-dot motion pattern, there is only one way to divide the individual motions into common and relative motion vectors as defined above.¹

These principles are illustrated in Fig. 1 with three motion patterns.

The actual motion patterns are shown in Column I. The dots move with constant velocity back and forth in their respective straight paths. The heavy and dotted arrows show the phase relations of the motions. In Columns II and III, the two phases of motion are shown according to the model. The arrows outside the rectangular frames illustrate the extracted common motion. Within the frames, the relative motions are shown. (Only the dots, not the frames, were shown in the experiments.) Note that the sum of the relative motion vectors equals zero.

The patterns shown in Fig. 1 are instances of relative motions studied in the experiments. In Pattern A, the dots move toward and away from a common point at which they would meet if their motion toward each other continued. This means that the relative velocity of each dot is proportional to its distance from the common point. The common point is identical with the

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Fig. 1. Application of the proposed vector model on three motion patterns.

point of gravity of the triangle constituted by the three dots. The relative motions of Pattern A can be considered as common since they are directed toward or away from a common point. In order to avoid confusion with the extracted common motion, they will be called *concurrent relative motions* (Börjesson & von Hofsten, 1972).

In Pattern B, the relative motions are parallel. Parallel relative motions of nonaligned dots in a three-dot motion pattern are directed toward or away from a common line. If the motions continue, the pattern will reach a position where the dots constitute a straight line, i.e., the common line. (There is a special case where the dots will be aligned only when the distance between one of the dots and the other two is infinite. This case need not concern us here.) The common line of Pattern B is indicated by a dotted line in Fig. 1. The relative motions of Pattern B can also be considered as common since they are directed toward or away from a common line. In this paper, they will be called *parallel relative motions*.

The relative motions of Pattern C are a *combination of concurrent and parallel relative motions*. Actually, the relative motions of Pattern C were constructed by adding the relative motions of Patterns A and B.

Since a general aim of the model is to allow prediction of perceived motion in depth by analyzing relative motions, the main independent variable in the present experiments is the kind of relative motions in the patterns. The model is further tested by using both one- and two-dimensional patterns, by changing the orientation of the patterns, and by varying the phase

relations of concurrent and parallel motion components in patterns with complex relative motions like those in Pattern C, Fig. 1.

Different magnitudes of concurrent and parallel relative motions were studied to see how perceived distance and angle of rotations in depth were affected.

EXPERIMENT I: PERCEIVED TRANSLATORY MOTION IN DEPTH

Börjesson and von Hofsten (1972) concluded that concurrent motions of two dots were perceived as translatory motion in depth when the motion pattern was two-dimensional. One-dimensional concurrent motions, however, were ambiguous for the eye and yielded several different percepts. Thus, if no common motion is added to the relative motions or if the common motion is parallel to the relative motions, the pattern is one-dimensional and ambiguous. If, however, the common motion added is not parallel to the relative motions, the pattern becomes two-dimensional and evokes stable depth percepts.

The aim of Experiment I was to test these conclusions with three-dot concurrent motion patterns. It was predicted that the common motion per se would have no effect on perceived translatory motion in depth, but that the dimensionality of the motion pattern would determine perceived depth; one-dimensional patterns yielding different percepts including motion in a frontoparallel plane and two-dimensional patterns yielding stable percepts of translation in depth.

The aim was to test further the effect of direction of the relative motions on perceived translatory motion in depth. In the motion patterns used by Börjesson and von Hofsten (1972), the relative motions were always horizontal. In Experiment I, motion patterns with both horizontal and vertical relative motions were included.

Method

Apparatus

A digital computer (Linc-8) was programmed to generate the motion patterns. The analog output of the computer was fed into an oscilloscope (Tectronix 565), which displayed the pattern by means of an optical device onto a translucent screen. In order to minimize cues of two-dimensionality from the screen, a collimator lens giving parallel light rays was placed between the screen and the S. This apparatus was used in all experiments.

Stimuli

The stimuli consisted of three dots moving back and forth, with constant velocity in their respective paths. All the motion patterns were instances of concurrent motions. Nine of the motion patterns used in Experiment I are illustrated in Fig. 2. The arrows show the motion paths of the dots, and the dotted and heavy ends of the arrows show the phase relations of the motions. In the headings of the columns are shown the relative motions for the patterns with the common motion (if any) extracted.

Fig. 2. The motion patterns used in Experiment I. The relative motions are shown in the headings of the columns, and the common motions, if any, in the headings of the rows.

relative common motions	A	B	C
A1	B1	C1
A2	B2	C2
A3	B3	C3

The greatest horizontal extension of the patterns of Column A subtended a visual angle of 3.8 deg and the smallest, a visual angle of 2.4 deg. Corresponding values for Column B were 3.6 and 2.4 deg and for Column C, 3.8 and 2.4 deg. The greatest vertical extension of the patterns in Column C was 3.8 deg and the smallest, 2.4 deg. In the headings of the rows are indicated occurrence and direction of the common motion. The common motions subtended a visual angle of 1.9 deg.

Besides the nine patterns described so far, another six were included in Experiment I, namely Patterns A1, B1, A2, B2, A3, and B3 in Fig. 2, rotated 90 deg clockwise in the frontoparallel plane.

Each phase of motion lasted for 3.5 sec. At the turning points, the dots disappeared for 0.7 sec. Thus, a full cycle was completed in 8.4 sec.

Viewing Conditions and Procedure

The S was seated with his head about 20 cm in front of the collimator lens and was told that three moving dots would appear on the screen. The S was asked to report verbally the kind of motions he perceived and, when uncertain as to how to express the percept, to show the motions with his hands. Further, he was asked not to fixate a particular dot. After three preliminary trials, the different motion patterns were presented once in randomized order. During each presentation, the room was darkened and the motion pattern appeared in a random phase of its cyclic course. The S looked binocularly at the pattern until he was ready to give his report. Then the room was lighted, the report written down, and following this the next pattern was presented.

Subjects

Of the 26 Ss who participated in Experiment I, 11 Ss saw the patterns presented in Fig. 2 and the remaining 15 Ss saw the 90-deg rotated versions of Patterns A1, B1, A2, B2, A3, and B3.

Results

The three dots were very often perceived as three dots attached to a rigid rod moving in space (Patterns A1, B1, A2, B2, A3, and B3 in Fig. 2) or as the corners of a rigid

triangle moving in space (Patterns C1, C2, and C3 in Fig. 2). Therefore, the reports were mainly classified in terms of motions of a rod or triangle. The following four response categories turned out to be appropriate: (P) Motions of three independent dots in a frontoparallel plane, or a rod/triangle moving in a frontoparallel plane and changing shape (PLANE). (D) Translatory motion in depth of a rod/triangle (DEPTH). (R) Rotation in depth of a rod/triangle (ROTATION). (DR) A simultaneous combination of Categories 2 and 3 (DEPTH + ROTATION).

In Table 1, the frequencies of different categories for each stimulus pattern are presented.

Table 1 shows that direction of the relative motions had no effect on perceived translatory motion in depth. With horizontal relative motions, Patterns A3 and B3

Table 1
Frequencies of Different Kinds of Percepts in Experiment I

		Horizontal Relative Motions (N = 11)		Vertical Relative Motions (N = 15)		(N = 11)
		A	B	A	B	C
No Common Motion	D*	3	2	7	5	11
	DR	2	3	5	3	0
	R	4	4	1	6	0
	P	2	2	2	1	0
Horizontal Common Motion	D	2	3	12	11	11
	DR	1	1	1	2	0
	R	6	5	2	1	0
	P	2	2	0	1	0
Vertical Common Motion	D	9	8	8	4	11
	DR	2	3	4	2	0
	R	0	0	3	4	0
	P	0	0	0	5	0

*D = depth, DR = depth + rotation, R = rotation, P = plane

Fig. 3. The motion patterns used in Experiment II. The relative motions are shown in the headings of the columns, and the common motions, if any, in the headings of the rows. The semidotted lines indicate the common lines of Patterns D and E.

evoked translatory motion in depth in 17 cases out of 22 (77%), and with vertical relative motions in 23 cases out of 30 (77%).

The presence of a common motion vector was not necessary for perceiving translatory motion in depth when the *relative* concurrent motions were two-dimensional (Patterns C1, C2, and C3). These patterns always evoked translatory motion in depth. However, patterns with one-dimensional *relative* motions were mainly perceived as a translatory motion in depth only if a common motion was added making the pattern two-dimensional (Patterns A3 and B3 in Fig. 1 and the rotated versions of these). One-dimensional motion patterns (Patterns A1, B1, A2, B2, and the rotated versions of these) received responses in all categories irrespective of the presence of a common motion.

Conclusions

It is concluded that the common motion per se is not necessary for perceiving translatory motion in depth. The common motion does have an effect, however, in cases where it makes the pattern two-dimensional. The dimensionality of the motion pattern determines the perception of concurrent motions. One-dimensional patterns are ambiguous for the eye and two-dimensional patterns yield stable percepts of translatory motion in depth. This conclusion was also drawn by Johansson (1964) and Börjesson and von Hofsten (1972). It is further concluded that horizontal and vertical relative motions have the same power to evoke perceived translation in depth.

EXPERIMENT II: PERCEIVED ROTARY MOTION IN DEPTH I

The next problem to be studied concerns conditions for perception of rotation in depth. Earlier investigations on depth perception from simple changing stimulus patterns have reported perceived rotation in depth (cf., for instance, Wallach & O'Connell, 1953; Johansson, 1964; Johansson & Jansson, 1968). The patterns

eliciting perceived rotation in these studies had proximally parallel motion paths. Börjesson and von Hofsten (1972), using two-dot patterns, studied whether the actual proximal motion paths had to be parallel or if parallelity of *relative* motions was a sufficient condition for perceived rotation in depth. Unambiguous percepts of rotation were obtained only when the actual proximal motion paths were parallel. However, two-dot motion patterns are in any moment of change aligned, i.e., it is always possible to connect the dots with a straight line. This property, which more complex motion patterns usually lack, may have been responsible for the result obtained by Börjesson and von Hofsten (1972).

The objective of Experiment II was to reexamine the question of whether parallelity of *relative* motions is a sufficient condition for perception of rotation in depth using patterns with the dots aligned as well as nonaligned.

Method

Stimuli

The motion patterns consisted of three dots moving back and forth in their respective paths. All motion patterns were instances of parallel *relative* motions. Only patterns lacking a common motion vector had dots moving in proximally parallel paths. The motions of the dots for some patterns are presented in Fig. 3. The heavy and the dotted ends of the arrows show the phase relations of the dots. The semidotted lines in the D and E patterns illustrate the common line. The maximum and minimum horizontal extension between the outermost dots of the A patterns were 3.8 and 3.0 deg of visual angle, respectively. Corresponding values for the B patterns were 3.8 and 2.4 deg, for the D patterns, 3.8 and 2.4 deg, and for the E patterns, 4.0 and 1.9 deg, respectively. The C patterns had a constant distance between the outermost dots of 3.3 deg.

The vertical separation of the upper and lower dots of the D and E patterns subtended a visual angle of 2.9 deg. The common motion subtended a visual angle of 1.9 deg. The 10 patterns were shown both oriented as in Fig. 3 and rotated 90 deg clockwise in the frontoparallel plane.

Each phase of motion lasted for 3.5 sec. At the turning points, the dots disappeared for 0.7 sec. Thus, a full cycle was completed in 8.4 sec.

Table 2
Frequencies of Different Kinds of Perceived Motion in Experiment II

Motion Pattern	Horizontal Relative Motions				Vertical Relative Motions			
	D*	DR	R	P	D	DR	R	P
A No Common	1	1	5	4	1	1	3	5
	4	1	6	0	2	0	5	3
B No Common	1	0	6	4	2	0	3	5
	2	2	6	1	4	0	1	5
C No Common	0	0	4	7	0	0	1	9
	0	0	4	7	0	0	0	10
D No Common	0	0	11	0	0	0	10	1
	0	0	9	2	0	0	7	4
E No Common	0	0	11	0	0	0	10	1
	0	0	11	0	0	0	10	1

*D = depth, DR = depth + rotation, R = rotation, P = plane

Viewing Conditions and Procedure

These were the same as in Experiment I.

Subjects

Eleven Ss participated in Experiment II.

Results

The reports were classified in the same four categories as in Experiment I. The frequencies of these categories are presented in Table 2. Table 2 shows that motion patterns consisting of aligned dots (A, B, and C patterns) did not yield stable percepts of rotation in depth in any of the conditions. The percepts differed in several ways. The three dots sometimes formed an elastic moving rod, sometimes a moving triangle in a recumbent position, and sometimes the dots were perceived to move independently, especially in the C patterns. Further, the C patterns were never perceived to move in depth, which might be due to the absence of relative motions between the outermost dots. Adding a common motion component, thus making the motion patterns two-dimensional, had very little systematic effect on the perceived event, although there was a slight increase in the number of reported translations in depth. The patterns still evoked unstable percepts. These kinds of motion patterns obviously contain too little information for the visual system.

The D and E patterns consisted of dots which were nonaligned. These patterns yielded stable percepts of rotation in depth of a triangle, irrespective of the presence of a common motion component. When the relative motions were directed away from the common line, the triangle was perceived to rotate toward the frontoparallel plane, and when they were directed toward the common line, the triangle was perceived to rotate toward the sagittal plane. The axis of rotation was always perceived as perpendicular to the relative motions.

A slight elasticity effect (object distortion) from the relative motions was obtained with all patterns used. Elasticity was more often perceived with vertical than with horizontal relative motions. This is in accordance with Green (1961), who found that rotating patterns were perceived as less coherent when the rotation axis was horizontal than when it was vertical.

Conclusions and Discussion

Concerning three-dot motion patterns with nonaligned dots, it is concluded from Experiment II that it is the parallelity of the *relative* motions and not the parallelity of the actual proximal motion paths that evokes stable percepts of rotation in depth. However, if the dots are aligned, rotation in depth will not be perceived unambiguously, irrespective of the presence of a common motion.

The visual angles used in Experiment II were relatively small, not exceeding 4.3 deg between any two dots of any pattern. Polar projections of the corners of a rigid triangle rotating in space around an axis parallel to the projective plane physically describes approximately parallel motions when the angle of projection is small. If this angle increases, the projected motions increasingly deviate from parallelity. It is possible, therefore, that the conclusions drawn from Experiment II cannot be generalized to motion patterns perceived under greater visual angles, but that other types of motions will determine stable percepts of rotation in depth in these cases.

EXPERIMENT III: PERCEIVED ROTARY MOTION IN DEPTH II

In Experiment II, it was shown that motion patterns with nonaligned dots were perceived as rotating in depth when the relative motions were parallel. However, the question remains whether *all* motion patterns with nonaligned dots and parallel relative motions are

Fig. 4. The motion patterns used in Experiment III. The relative motions are shown in the headings of the columns, and the common motions, if any, in the headings of the rows. The semidotted lines indicate the common lines.

perceived to rotate in depth. The actual motion patterns used in Experiment II (the D and E patterns in Fig. 3) had two properties in common which might be of importance for the perception of motion in depth.

First, the common line is perpendicular to the direction of the parallel motions (or approximately perpendicular). The question is whether the orientation of the common line is of any importance for the perception of rotation in depth.

Secondly, the distance between the two left dots is invariant for the D patterns and approximately invariant for the E patterns. The question is whether the constancy of distance between pairs of dots in a three-dot motion pattern is a necessary condition for perceived rotation in depth.

An especially interesting case of parallel relative motions in three-dot patterns is when all the distances between the dots simultaneously decrease or increase. An analysis based on changes of the length of sides of a triangle might predict translatory motion in depth in this case. The present model, however, predicts perceived rotation in depth, determined by the parallel relative motions.

Method

Stimuli

The stimuli consisted of three dots moving back and forth with a constant velocity in their respective motion paths. Some of the motion patterns used in Experiment III are presented in Fig. 4.

The common line is shown by the semidotted lines in Fig. 4. Patterns A-D in Fig. 4 differed in two respects. First, the A and B patterns each have two dots which did not move relative to each other, i.e., the distance between two of the dots in these patterns did not change. In the C and D patterns, all the dots moved relative to each other. In the D patterns, all the distances between the dots were simultaneously increasing or decreasing.

Second, the A and D patterns had a common line which was perpendicular to the relative motions. This was not the case with the B and C patterns.

The maximum horizontal extension of the outermost dots subtended a visual angle of 3.8 deg, and the minimum horizontal extension of the outermost dots subtended a visual angle of 2.4 deg for the A patterns. Corresponding values for the C

patterns were 3.8 and 2.9 deg, and for the D patterns, 4.8 and 1.9 deg. The B patterns had a constant distance between the outermost dots, subtending a visual angle of 3.3 deg. The distance between the upper and lower dots in all patterns was constant, subtending a visual angle of 2.9 deg. The common motion subtended a visual angle of 1.0 deg. The eight motion patterns in Fig. 4 were presented with two different orientations. They were shown either as in Fig. 4 or were rotated 90 deg clockwise in the frontoparallel plane, in which case the parallel motions were vertical and any common motions were horizontal. Thus, a total of 16 patterns were presented in Experiment III.

Each phase of motion lasted for 5.9 sec. The dots disappeared for 0.7 sec at the turning points. Thus, a full cycle was complete in 13.2 sec.

Viewing Conditions and Procedure

These were the same as in Experiment I.

Subjects

Eleven Ss participated in Experiment III.

Results

The reports were classified in the same response categories as in Experiment I. Since the common motion had no effect (the patterns with a common vector eliciting a total of 58 percepts of rotation and those without a common vector, a total of 62), the reports from patterns with and without common motion vectors were combined. In Table 3, the frequencies of reports in the four response categories are summarized over Ss for each type of pattern and orientation. Since only parallel relative motions were used, as expected the most common report was perceived rotation in depth.

The A and B patterns, unlike the C and D patterns, each had two dots which did not move relative to each other. A comparison of the results from the A and B patterns and the C and D patterns shows that the former yielded a total of 60 reports of perceived rotation in depth and 26 reports of perceived motion in the frontoparallel plane. The corresponding frequencies for the C and D patterns are 60 and 24. Thus, the A and B patterns did not differ from the C and D patterns as to the probability of evoking perceived rotation. It should

be noted that for the D patterns, in which all distances between the dots were simultaneously increasing or decreasing, only 4 out of 44 percepts included some kind of translatory motion in depth.

The A and D patterns with common lines perpendicular to the relative motions evoked a total of 70 percepts of rotation in depth and 13 percepts of motion in a frontoparallel plane. Corresponding frequencies for the B and C patterns, with common lines not perpendicular to the relative motions, were 50 and 37.

Horizontal relative motions yielded a total of 68 reports of perceived rotation and 18 reports of perceived motion in a frontoparallel plane. Corresponding frequencies for vertical relative motions were 51 and 32. This is the same effect as occurred in Experiment II. Finally, there is a clear interaction between the relative orientation of the common line and the direction of the relative motions. Thus, the effect of these variables is due mainly to the condition of vertical parallel motions and oblique common line relative to the parallel motions. In this condition, there were 18 reports of rotation in depth and 25 reports of motion in a frontoparallel plane.

Conclusion

It is concluded from Experiment III that parallel relative motions generally evoke perceived rotation in depth whether or not the distance between any pair of motion elements is constant. As pointed out earlier, this conclusion is limited to motion patterns perceived under small visual angles (less than about 5 deg).

The orientation of the common line has a slight effect in that a common line perpendicular to the relative motions favors perceived rotation in depth. It should be noted here that when perceiving rotation in depth from patterns lacking perpendicular common lines, the Ss also reported that the perceived triangle was always tilted in depth and never reached the frontoparallel plane.

Taking Experiments II and III together, it is concluded that there are small but reliable effects of the direction of parallel relative motions in three-dot motion patterns on perceived motion. Horizontal relative motions favor perceived rotation in depth.

EXPERIMENT IV: PERCEIVED COMBINATION OF TRANSLATORY AND ROTARY MOTION IN DEPTH

The previous experiments have considered the perception of translatory motion in depth resulting from concurrent motions and the perception of rotation in depth resulting from parallel relative motions. Stimuli reaching the eye are more complex, often yielding percepts of simultaneous translation and rotation in depth. Johansson (1964), using rectangular patterns changing in shape, concluded that the visual system

Table 3
Frequencies of Different Kinds of Percepts in Experiment III

Pat-tern	Relative Motions	D*	DR	R	P
A	Horizontal	0	1	20	1
	Vertical	0	0	18	4
B	Horizontal	0	0	14	8
	Vertical	0	1	8	13
C	Horizontal	0	0	18	4
	Vertical	0	0	10	12
D	Horizontal	0	1	16	5
	Vertical	1	2	16	3

*D = depth, DR = depth + rotation, R = rotation, P = plane

extracts concurrent motions yielding translatory motions in depth and residual motions yielding simultaneous rotation in depth or change of shape. Börjesson and von Hofsten (1972), using two-dot motion patterns, failed to get stable percepts of simultaneous translation and rotation in depth. This result was probably due to the fact that when the common motion is removed, the *relative* motions of two dots are always parallel. With three-dot motion patterns, it is possible to get parallel as well as nonparallel relative motions.

Taking the results from Experiments I-III into account, it was predicted that the visual system extracts concurrent and parallel motion components yielding simultaneously perceived translation and rotation in depth if this is geometrically possible. Whenever this occurs, there are two sets of parallel and concurrent motions which will result in the motion pattern. Which of these sets does the visual system choose? It was predicted that the set chosen would be the one that had the smallest relative magnitude of concurrent motion. This prediction is in accord with Johansson's (1964) conclusion that the perceived translation in depth is determined by the smallest relative change (the principle of least change).

The motion patterns used in Experiment IV are represented in Fig. 5 with only one of the two phases of motion indicated. The dots moved back and forth in their respective paths. The actual motion patterns presented in the experiment are illustrated in Column I. The two different sets of concurrent and parallel relative motions are shown in Columns II and III. For clarity, dotted lines drawn toward the common point indicate the concurrent motion components and semidotted lines indicating the common line for the parallel motions.

The predictions will be verified if Pattern A is perceived to move according to the relative motions in Column II in Fig. 5, i.e., to recede and simultaneously to rotate toward the sagittal plane around a horizontal axis. If Pattern A apparently approaches rather than recedes, the pattern will be perceived to rotate toward the frontoparallel plane. The same predictions were made for Pattern B. In both these patterns, it is possible to

Fig. 5. The motion patterns used in Experiment IV (Column I) and the two analyses of these in terms of concurrent and parallel motion components (Columns II and III).

extract a concurrent and a parallel motion component which are in the same phase, i.e., the concurrent motions are directed toward the common point and the parallel motions toward the common line simultaneously (see Column II in Fig. 5).

In order to find out whether phase relationships were of importance for the perceptual extraction of motion components, two patterns, where it was not possible to extract concurrent and parallel motion components which were in phase (Patterns C and D), were included. Pattern C was constructed to produce two sets of motion components with concurrent components of the same relative magnitude. Thus, according to the predictions, it is as probable that the pair of motion components in Column II will be extracted as those in Column III, yielding perceived rotation around a horizontal or a vertical axis, respectively. Finally, according to the predictions, Pattern D will be perceived to move according to the motion components in Column III, which has the concurrent motion component with the smaller relative magnitude. Thus, Pattern D will be perceived to rotate around a vertical axis. When perceived to recede, Pattern D will be perceived to rotate toward the frontoparallel plane, and when perceived to approach, to rotate toward the sagittal plane.

Method

Stimuli

The motion patterns used in Experiment IV are shown in Fig. 5. The maximum and minimum horizontal extension of the outermost dots in Pattern A subtended visual angles of 4.3 and 3.0 deg. respectively. Corresponding values for Pattern B were

1.9 and 1.3 deg. for Pattern C, 3.6 and 2.9 deg. and for Pattern D, 4.3 and 2.9 deg. The maximum and minimum vertical extension between the upper and lower dots subtended visual angles of 3.8 and 3.0 deg. respectively, for Pattern A. Corresponding values for Pattern B were 3.8 and 1.3 deg. for Pattern C, 3.8 and 2.6 deg. and for Pattern D, 3.8 and 2.6 deg. Each pattern was presented in two versions: one as in Fig. 5 and one rotated 90 deg clockwise in the frontoparallel plane. Thus, there were eight different stimulus patterns.

Each phase of motion lasted for 5.9 sec. At the turning points, the dots disappeared for 0.7 sec. Thus, a full cycle was completed in 13.2 sec.

Viewing Conditions and Procedure

These were the same as in Experiment I, except that each stimulus pattern was presented twice in randomized order. Experiment IV was run at three different sessions. In the first session, the different conditions of Patterns A and B were presented; in the second session, the two conditions of Pattern C were presented; and in the third session, the two conditions of Pattern D were presented.

Subjects

Ten Ss participated in each session. Four of these Ss participated in all three sessions, making a total of 22 Ss.

Results

The reports were classified in the same four categories as in Experiment I. The different frequencies summarized over Ss and orientation of patterns are presented for each pattern in Table 4. Since the patterns were sometimes perceived as elastic and changing shape when moving, the number of reports of elasticity for each pattern and type of perceived motion are presented within parentheses in Table 4.

As predicted, Patterns A and B were generally perceived to translate and rotate in depth simultaneously. The perceived relationships between translation and rotation and the perceived axis of rotation agreed with the predictions for these patterns.

Patterns C and D were not perceived as predicted. On the contrary, these patterns were mainly perceived to rotate in depth and change shape. Thus, in 16 out of 25 reports of rotation in depth, a simultaneously perceived elasticity was reported for Pattern C. Corresponding frequencies for Pattern D were 27 out of 33. Concerning perceived orientation of the axis of rotation, 6 reports were in agreement with Column II in Fig. 5 and 13 were in agreement with Column III, while 6 reports indicated orientation of rotation axis for Pattern C other than those predicted. Pattern D was perceived to rotate around the axis predicted in Column III in 22 cases out of 36.

Conclusions and Discussion

A basic hypothesis in Experiment IV stated that the set with the smallest relative magnitude of the concurrent component was chosen by the visual system, concurrent and parallel motions yielding apparent translation and rotation in depth, respectively. This hypothesis was not confirmed, since Patterns C and D generally were perceived as elastic and not to move translatory in depth.

The results of Experiment IV are theoretically interesting, since they demand a reformulation of the principle of least change. The data suggest that *the visual system extracts the set in which the concurrent and the parallel components are in phase*. For Patterns A and B, where it is geometrically possible to extract such a set, the principle of least concurrency and the principle of phase relations give the same predictions, and these were confirmed by the data. For Patterns C and D, a set in which the concurrency and the parallel components are in phase is not geometrically possible. The fact that Patterns C and D did not evoke apparent translation in depth thus supports the interpretation that phase relations are of critical importance.

Only four patterns were used in Experiment IV, and the principle of phase relations needs to be tested further. Data reported by Johansson (1964) supply support for the present principle. He found that patterns with concurrent and parallel components in phase, such as a square shrinking into a rectangle, were generally perceived to translate and rotate in depth. A rectangle growing in one dimension and shrinking in the other cannot be split up in concurrent and parallel components in phase. The latter pattern was as often perceived to change shape in a frontoparallel plane as to move translatory in depth.

Table 4
Frequencies of Different Kinds of Perceived Motions in Experiment IV†

Motion Pattern	D*	DR	R	P
A	2 (2)	38 (1)	0	0
B	5 (5)	32 (4)	0	3
C	2 (2)	0	25 (12)	13
D	0	3 (1)	33 (27)	4

*D = depth, DR = depth + rotation, R = rotation, P = plane

†The number of reported elasticity percepts is shown within parentheses.

EXPERIMENT V: MAGNITUDE OF PERCEIVED TRANSLATION AND ROTATION IN DEPTH

It was concluded in Experiment IV that the visual system extracts the set of motion components in which the concurrent and the parallel motions are in phase, i.e., move simultaneously toward or away from the common point and the common line, respectively. This conclusion was based on reports of perceived orientation of rotation axis and perceived phase relations between translation in depth and rotation. The purpose of Experiment V was to test further whether or not the visual system extracts the concurrent and parallel motion components that are predicted by the model. In this test, the predictions of the magnitude, as well as the type and direction of relative motion components, may be considered. According to Marmolin and Ulfberg (1967), the magnitude of concurrent motions affects the perceived distance of translatory motion in depth; the greater the magnitude of concurrent motions, the greater is the perceived distance of motion in depth. Epstein, Jansson, and Johansson (1968), using rotating ellipses, found greater perceived angles of oscillation with greater relative magnitude of the parallel motions. This leads to the following predictions: First, the set of motion components in which the concurrent and the relative motions are in phase will always be extracted by the visual system. When receding from the S, the pattern will rotate toward the sagittal plane, and when approaching, toward the frontoparallel plane. Second, patterns with greater magnitude of concurrent motion components will be perceived to move a greater distance in depth, and patterns with greater relative magnitude of parallel motion components will be perceived to complete a greater angle of rotation in depth. Finally, two patterns with the same relative magnitude of the concurrent motion components will be perceived to move the same distance in depth, and patterns with the same relative magnitude of the parallel motion components will be perceived to complete the same angle of rotation in depth. It should be noted that slight deviations from the last prediction might occur due to the effects of residual motions on perceived translatory motion in depth.

Fig. 6. The motion patterns used in Experiment V (Column I) and the predicted analysis of concurrent (Column II) and parallel (Column III) motions.

reported by Marmolin and Ulfberg (1967). Their result implies that in case of equal magnitude of concurrent motion components, the pattern with the greatest *parallel* relative motion component will have a tendency to be perceived as moving farther in depth.

Method

Stimuli

The motion patterns used in Experiment V are presented in Fig. 6, Column I. In Columns II and III are presented the concurrent and parallel motion components that will be extracted according to the predictions. There are two magnitudes of concurrent motion components: large in Patterns A and B, small in Patterns C and D. There are also two magnitudes of parallel motion components: large in Patterns A and C, small in Patterns B and D.

The maximum horizontal extension for all patterns was 4.5 deg, and the maximum vertical extension was 6.2 deg of visual angle. The minimum horizontal extension for Pattern A subtended 1.0 deg, for Pattern B, 1.7 deg, for Pattern C, 1.7 deg, and for Pattern D, 2.4 deg of visual angle. The minimum vertical extension for Pattern A subtended 3.3 deg, for Pattern B, 3.3 deg, for Pattern C, 4.4 deg, and for Pattern D, 4.4 deg of visual angle.

Each phase of motion lasted for 5.9 sec. At the turning points, the dots disappeared for 0.7 sec. Thus, a full cycle was completed in 13.2 sec.

Viewing Conditions

These were the same as in Experiment I.

Procedure

In four preliminary trials, Patterns A-D were presented in

randomized order for each S. After that, the S was asked to report what kind of event he had perceived. Then each of the six possible pairs of the four patterns was presented in the order of first pattern-second pattern-first pattern-second pattern. After thus seeing the pair twice, the S reported which pattern, the first or the second, covered the greatest motion distance in depth and which pattern completed the greatest angle of rotation in depth. If the S could not detect any difference in depth or rotation, he was allowed to report that the patterns were alike in the relevant aspect. The order of presentation of patterns within each pair was counterbalanced in the experiment.

Subjects

Ten Ss participated in Experiment V.

Results

One S generally perceived the patterns as elastic and not moving in depth. This S was excluded from the data treatment. The other nine Ss reported, with very few exceptions, a translatory motion in depth and a simultaneous rotation in depth of a rigid triangle. The triangle was perceived to recede when rotating toward the sagittal plane and to approach when rotating toward the frontoparallel plane. The frequencies of judgments of which pattern had the greatest translatory motion in depth and which pattern had the greatest rotation in depth within each pair are summarized over Ss in Table 5. According to the predictions, the numbers italicized in Table 5 should be equal to 9. There were two notable deviations from the predictions in Table 5. Only three Ss reported the perceived distance of translatory motion in depth as equal for Patterns A and B, while five Ss reported the distance in depth covered by Pattern A as greater. However, this result is in accordance with the findings reported by Marmolin and Ulfberg (1967), that residual vectors affect perceived translatory motion in depth; the greater the residual vector, the greater is the perceived distance of translatory motion in depth. As has been noted, Pattern A has a greater relative magnitude of the parallel motion component than Pattern B. A corresponding effect seems to be present in the case of perceived angle of rotation in depth, the magnitude of this angle being affected by the concurrent motions. Thus, only two Ss reported the rotation in depth as equal for Patterns B

Table 5
Frequencies of the Different Judgments of Translatory Motion and Rotation in Depth Summarized Over Ss for Each Pair of Patterns

Pairs of Patterns Compared	Depth			Rotation		
	I > II	I = II	I < II	I > II	I = II	I < II
A-B	5	3	1	8	1	0
A-C	9	0	0	1	8	0
A-D	9	0	0	9	0	0
B-C	9	0	0	1	2	6
B-D	9	0	0	5	2	2
C-D	1	7	1	9	0	0

and D and five Ss reported Pattern B, which had the greater relative magnitude of concurrent motion component, to cover a greater angle of rotation in depth.

Conclusions

It is concluded from Experiment V that the relative motion components that are predicted by the model are, indeed, extracted by the visual system.

SUMMARY OF RESULTS AND DISCUSSION

The three-dot motion patterns used in this investigation nearly always evoked perception of units moving in space. Motion patterns with aligned dots were most often perceived as rods, the ends of which were defined by the outermost dots, and those with nonaligned dots were perceived as triangles, the corners of which were defined by the dots. Further, motion patterns with nonaligned dots yielded stable percepts much more consistently than those with aligned dots. It is concluded from the results that three-dot motion patterns with aligned dots lack information for the visual system, supplied by other three-dot motion patterns. Therefore, only patterns with nonaligned dots are considered in the following discussion.

Under most conditions, the motion patterns gave stable percepts of motion in depth. The properties of the proximal pattern determined the nature of perceived motion in depth as follows: (1) Translatory motion in depth is evoked by concurrent relative motions. The simultaneous increase or decrease of the distances between the three dots constitute a necessary but not a sufficient condition for evoking translatory motion in depth. (2) Rotation in depth is evoked by parallel relative motions, irrespective of constancy of distance between any pair of motion elements. This conclusion is limited to small visual angles (less than 5 deg). The stability of the perceived rotation in depth is increased if the common line of the motion pattern is perpendicular to the relative motions and also if the direction of the relative motions is horizontal. (3) Under certain conditions, the visual system is able to split up complex motion patterns into simple relative motion subsets, i.e., into concurrent and parallel relative motions. Thus, a simultaneous translation and rotation in depth will be perceived if the following two conditions are fulfilled. First, the motion pattern should be the vector algebraic sum of one concurrent relative motion component and one parallel relative motion component. Secondly, the two motion components should be in phase, i.e., simultaneously moving toward or away from the common point and the common line, respectively.

The motions in space of rigid objects can be analyzed in terms of translations along and rotations around axes in each of the three dimensions of space. These six types

of motions exhaust the possibilities of mechanical movements (Gibson, 1957). The present model accounts for the perception of translation in all three dimensions of space: frontoparallel translations by the extraction of common motion, and translation in depth by the extraction of concurrent relative motions. It also accounts for the perception of rotation around frontoparallel axes by the extraction of parallel relative motions. The model does not, however, say anything about perception of rotation around the line of sight. The next natural step will be to find out what kinds of motion components are extracted by the visual system in the perception of rotation around the line of sight.

When this has been done, the model will provide concepts in terms of different motion components which correspond to all possible types of perceived rigid motion in space.

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NOTE

1. If the dots are regarded as the corners of a triangle, it can be mathematically proven that the center of gravity of this triangle is independent of the relative motions of the dots, even if the proximal triangle changes shape and/or size during the motion. This follows from the fact that the sum of the relative motions equals zero.

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