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On the Relation Between Time and Space in the Visual Discrimination of Velocity

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Is the perception of velocity determined by the prior discrimination of spatial and temporal distances? Two experiments sought to answer this question by comparing the discriminabilities of moving stimuli varied in spatial extent, temporal duration, or in redundant combinations of both variables. The subject's task was to identify which of two alternative stimuli was presented on each trial. A set of four stimuli was constructed from two values of spatial extent and two values of temporal duration. Separate conditions required discrimination of each of the six possible pairs of these stimuli. Experiment 1 examined continuous motion and Experiment 2 examined apparent motion for stimuli with short (50 versus 65 msec) and with long (500 versus 650 msec) interstimulus intervals. With continuous motion and with good apparent motion (short intervals), the discrimination between the different-velocity bivariate pairs was too accurate to be attributed only to discriminations of the spatial and temporal extents of the motion. This did not occur with poor apparent motion. Evidently, time and space are perceptually related.

A fundamental and ancient question about the perception of moving stimuli is whether velocity is perceived as a primary attribute of visual encoding or whether it is a secondary characteristic derived from the prior discrimination of spatial and temporal positions. In physical terms, velocity is simply the rate of change in spatial position. Average velocity is thus given by $\bar{v} = \Delta s/\Delta t$, where Δs and Δt are the spatial and temporal distances between two successive positions of a moving object. Since there are only two independent terms in this equation, direct sensory information about velocity is unnecessary; knowledge of velocity might be derived from discriminations of spatial and temporal positions. The empirical question might be phrased in several alternative ways, but one useful way is in terms of the relative accuracy of discriminations of stimuli differing in spatial, temporal, and velocity variables.

Support for the hypothesis that velocity is a directly perceived attribute of stimulation has been taken from several lines of evidence: (a) Apparent motion can be produced by the successive presentation of two discrete stimuli at an appropriate interstimulus interval (Wertheimer, 1912/1966; also see Boring, 1942, and Kolers, 1972).[1] (b) Motion is a sufficient cue for the discrimination of otherwise undifferentiated spatial patterns (Bell & Lappin, 1973; Biederman-Thorson, Thorson, & Lange, 1971; Gibson, 1965). (c) The minimum detectable target velocity at short exposure durations is dependent upon total energy, the product of luminance and duration

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[1] This inference relies on certain assumptions about the validity of phenomenological evidence: Since a compelling subjective impression of motion can be produced by stimuli that are known by the observer to be in two discrete spatial and temporal positions, then the subjective experience is thought to arise directly from sensory processes. The same premises, however, could lead to the opposite conclusion: Since the observer has prior knowledge of the successive spatial and temporal positions of the stimulus, direct sensory information about velocity is unnecessary in this case.

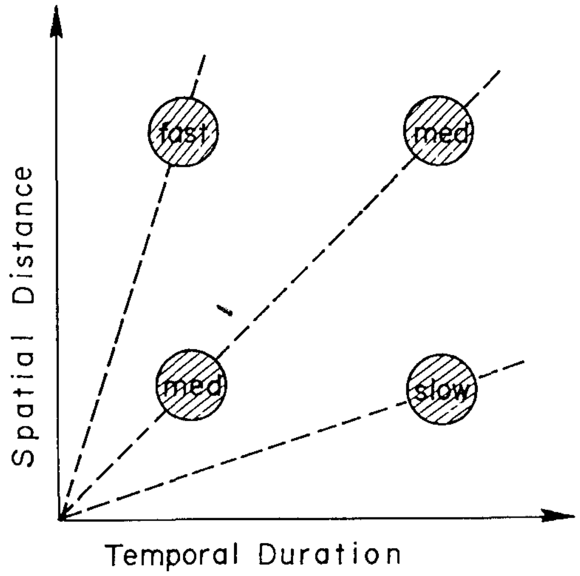

FIGURE 1. Schematic illustration of the stimulus set in terms of the space-time plots of each of the four alternative stimuli. (The velocity is determined by the slope of the dashed line from the origin to the stimulus point [although in the actual experiments these would have been much more similar, since the spatial and temporal values were proportional to the numbers 8 and 9 in Experiment 1 and the numbers 10 and 13 in Experiment 2].)

(Brown, 1955; Leibowitz, 1955b), is unaffected by the addition of reference cues to spatial position (Leibowitz, 1955a), and seems therefore to be based upon "elementary retinal" processes. (d) Extended viewing of a continuously moving pattern produces an aftereffect of subjective motion of a stationary pattern in the opposite direction (see Boring, 1942) and a lowered sensitivity to motion in the same direction at the same velocity (Pantle & Sekuler, 1968; Sekuler & Pantle, 1967). (e) Magnitude estimations of subjective velocity are described by a power function with an exponent that is larger than the exponent for magnitude estimations of the spatial and temporal extent of the motion (Mashour, 1964). With the exception of the experiments by Mashour and Biederman-Thorson et al., however, most of these studies have not controlled or measured the spatial and temporal discriminations on which the perception of motion might be based. Nevertheless, they tend to indicate that prior discriminations of time and space are not necessary prerequisites for the perception of motion.

In contrast, several discrimination experiments suggest that spatial and temporal discriminations are more accurate than those of velocity and are therefore likely to govern the perception of motion under many conditions. The most relevant study was conducted by Mandriota, Mintz, and Notterman (1962), who measured difference thresholds for velocity of continuous motion under conditions differing in the availability of spatial and temporal cues. The thresholds for velocity discrimination were lowest under the isochronal condition (duration constant and distance varied), slightly higher under the isometric condition (distance constant and duration varied), and were highest under the heterodimensional condition (duration and distance both varied) which presumably required discrimination primarily by velocity. Similarly, Kinchla and Allan (1969) concluded that detection of motion in successive light flashes can be represented as a spatial discrimination task in which accuracy is limited by memory for the initial stimulus position. Kinchla and Allan obtained an invariant estimate of the temporal rate of decay of this hypothesized memory for spatial position from a variety of tasks.

Current research thus offers conflicting indications about the role of spatial and temporal cues in the perception of motion. The present study was designed to determine the contributions of space, time, and velocity to discriminations between moving stimuli.

Subjects were asked to identify which of two alternative stimuli was presented on each trial. The experimental condition was determined by the particular pair of stimuli that was presented in a given block of trials. The stimulus set consisted of four stimuli varied in two values of spatial distance and two values of temporal duration; in separate conditions the two alternative stimuli were each of the six possible pairs that could be obtained from this set. A schematic description of the stimulus set is given in Figure 1. As may be seen, two of the pairs provided a variable temporal duration with constant spatial distance, two others provided a variable spatial distance with constant duration, and the remaining two pairs varied in both the spatial and temporal dimensions with one pair having a constant velocity and the other pair providing the maximum variation in velocity. The specific question asked in these experiments concerns the accuracy of discrimination for the two bivariate stimulus pairs in relation to the discrimination for the univariate stimulus pairs (considering the spatial and temporal extents of the motion as the two stimulus variables).

Several alternative predictions can be given for the level of discrimination produced by the redundant combination of the spatial and temporal variables. One family of predictions can be generated by the general class of linear models for integration of the spatial and temporal information. The general assumption in this class of models is that discriminations of velocity are dependent on the discriminabilities of the spatial and temporal positions of the moving stimulus. One familiar model in this class postulates that the spatial and temporal dimensions are perceptually independent (in the sense that errors of discrimination are stochastically independent or uncorrelated), so that both dimensions simultaneously contribute to discriminations between unitary stimuli compounded from redundant combinations of the two dimensions. Discriminations between the bivariate pairs of stimuli in this study may then be predicted from the spatial and temporal discriminations by the Pythagorean formula for calculating distance in a two-dimensional Euclidean space. Specifically, if we let $D(S)$ and $D(T)$ represent the discriminal distances[2] between two univariate stimuli differing along the spatial and temporal dimensions, respectively, and if $\hat{D}(V)$ and $\hat{D}(E)$ are the predicted discriminations for the bivariate pairs with variable velocity and equal velocity, respectively, then we can write the prediction as

$$\hat{D}(V) = \hat{D}(E) = [D^2(S) + D^2(T)]^{\frac{1}{2}}. \quad (1)$$

We will refer to this prediction as the *perceptual independence model.*

The assumption that the spatial and temporal dimensions are perceptually independent can be relaxed to include the more general case in which they are perceptually correlated, corresponding to a perceptual space in which the spatial and temporal vectors meet at an obtuse or acute angle.

If perceived spatial extent and perceived temporal duration were inversely related by the visual system, then differences in velocity would be magnified: The perceptual space for the four stimuli shown in Figure 1 would thus be changed from a rectangle, as in the perceptual independence model, into a parallelogram, with the longer diagonal between the different-velocity bivariate pair extended and with the diagonal between the equal-velocity pair correspondingly compressed. By using the law of cosines to express the two bivariate distances and then substituting for the unknown angle between the spatial and temporal vectors, we obtain the following prediction:

$$\hat{D}(V) = [2D^2(S) + 2D^2(T) - D^2(E)]^{\frac{1}{2}}. \quad (2)$$

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[2] We used the measure $-ln\eta$ from Luce's choice theory as the measure of discriminal distance:

$$D(s_1, s_2) \equiv -ln\,\eta = -1/2 \log_e \left[\frac{P(r_2|s_1)P(r_1|s_2)}{P(r_1|s_1)P(r_2|s_2)}\right].$$

This measure is very similar to the measure d' from signal detection theory—in terms of the receiver-operating-characteristic curve and in terms of the implied distributions of sensory events associated with the two response alternatives. The numerical values are approximate scalar transforms of d'. Similarly $-ln\eta$ is a ratio scale of discriminability that may be interpreted as a measure of distance between the two stimulus alternatives. See Luce (1963) for further details. The main assumption in using this measure to test the perceptual independence of time and space is that discrimination accuracy is determined by the amount of overlap of two approximately logistic distributions of perceptual events associated respectively with the two stimulus alternatives. If two variables are stochastically independent, then the variance of their sum is equal to the sum of their variance. Accordingly, we have $D^2(S+T) = D^2(S)+D^2(T)$ as a test of the assumption that the discriminations of time and space are perceptually independent. The finding in Experiment 2 that the equal-velocity discriminations were close to this prediction provides partial support for this measurement model.

We shall refer to this as the *correlated dimensions model.*

If, however, discriminations between stimuli moving at different velocities are not based on linear combinations of perceptual information about spatial and temporal positions, then the above predictions may not hold. If velocity is a perceptually unique attribute that is not dependent on discriminations of spatial and temporal distances, then the accuracy of discrimination of the bivariate pair of stimuli with different velocities is likely to exceed the predictions of the linear models. Additionally, the discriminability of the equal-velocity pair might be poorer than predicted by the perceptual independence model if velocity contributes to the discrimination of the univariate stimulus pairs. Such nonlinear effects produced by redundant combinations of two physically distinct variables have been demonstrated in a few previous experiments—e.g., varying both the height and width of rectangles produced forms that were more easily identified by their shape and area than by the height and width variables per se (Weintraub, 1971). One interpretation of these nonlinear effects is that the redundant variables have combined to produce a new perceptual dimension based on their relationship within a given stimulus (Garner, 1972). Whereas previous examples of these nonlinear effects have involved relations between physically similar variables, in the present case time and space are different "fundamental" physical variables. The question of whether velocity is perceived as a primary attribute of stimulation may be regarded as a question of whether a unique perceptual dimension is formed by the relationship between the spatial and temporal extents of moving stimuli.

EXPERIMENT 1

The purpose of this experiment was to determine whether discriminations of continuous (rather than apparent) motion are based on discriminations of the spatial distance and temporal duration of the motion or, alternatively, whether unique perceptual information can be obtained about the velocity of motion. This experiment differed from that of Mandriota et al. (1962) in two respects: (a) Whereas Mandriota et al. adjusted the physical discriminabilities of their stimuli in order to determine a "just noticeable difference" in physical units, we held the physical variables constant and measured the accuracy of discrimination for each pair of stimuli. One advantage of the latter strategy is that it permits the evaluation of several quantitative models for the gain in discrimination accuracy produced by redundant combinations of stimulus variables. (b) More importantly, we randomly varied the initial and final positions of the moving stimuli in order to prevent discriminating spatial distance by only the final position, which was apparently possible in the experiment of Mandriota et al.

Method

Stimuli. The stimuli were small spots of light, continuously moving at a constant velocity for some fixed distance and duration. These stimuli were displayed on a cathode-ray tube display scope (Tektronix 604), equipped with a rapidly decaying phosphor (P-15), and controlled by a small digital computer (PDP-8/I). The stimuli were viewed in a dimly lighted room in which the surface and sides of the display scope were clearly visible. (This should enhance the discriminability and salience of the spatial positions of the stimuli.) The viewing distance was approximately 127 cm, resulting in a visual angle of about 4.5° subtended by the face of the display scope.

The horizontal and vertical positions of the stimuli were randomly varied from trial to trial. There were 64 alternative starting positions, roughly evenly distributed in the horizontal and vertical dimensions. The direction of motion was always horizontal. When the initial position was to the right or center of the scope, the movement was right to left, and when the initial position was on the left, the movement was from left to right.

As shown schematically in Figure 1, there were four alternative stimuli composed of two distances and two durations of motion. The ratio of shorter to longer distances and shorter to longer durations was 8:9—so that two of the stimuli had the same velocity, while the velocities of the other two stimuli were 8/9 and 9/8 of this value. The horizontal distances of motion were either 192 or 216 of the 512 possible locations on the face of the scope. At the particular viewing distance used, these distances of motion corresponded to approximately 90 or 101 minutes of visual angle. The total duration of motion was either 541 or 609 msec. (Due to a computational error in inappropriately rounding one figure, the total duration for the stimulus with the shorter distance and

TABLE 1

PERCENTAGES OF CORRECT RESPONSES FOR EACH DISCRIMINATION CONDITION IN EXPERIMENT 1

		Discrimination condition					
		Time		Space		Bivariate	
Subject	Session	Short space	Long space	Short time	Long time	Equal velocity	Different velocity
DH	A	64	66	60	60	60	77
	B	68	66	66	59	50	87
JH	A	62	66	60	64	60	90
	B	72	68	60	60	56	86
SN	A	66	65	70	66	66	78
	B	72	66	58	69	68	90
HT	A	69	74	70	72	56	90
	B	70	76	70	69	67	90
JT	A	78	69	62	72	68	88
	B	74	67	72	68	56	88
MW	A	74	66	72	77	68	86
	B	80	78	70	78	74	94
M		70.7	68.8	66.0	67.9	62.5	87.0

longer duration was actually 616 instead of 609 msec.) The resulting velocities were thus approximately 146, 166, and 187 minutes of angle per second. As the stimulus moved across the face of the scope, each of the 192 or 216 consecutive positions was activated in sequence. To simulate the physical characteristics of a continuously moving spot of light of constant intensity, the number of times each position was activated was inversely proportional to the velocity of the stimulus—either 164 (this should have been 162 and accounts for the longer duration), 144, or 128 times for each point, with a constant 19.5-microsec interval between pulses to the same point and an additional 12-microsec interval between adjacent points.

Subjects. The subjects were six male students at Vanderbilt University who served as paid volunteers.

Procedure. There were six experimental conditions, each requiring discrimination between one of the six pairs of four stimuli, as illustrated schematically in Figure 1. Two conditions required temporal discriminations between stimuli with the same spatial extent (either short or long) and different durations; two conditions required spatial discriminations between stimuli with the same temporal duration (either short or long) and different spatial extents; and two bivariate conditions required discrimination between stimuli differing redundantly in both distance and duration, with the velocities of the two stimuli being either equal or different. A given experimental session was devoted to either the spatial, temporal, or bivariate discriminations, and both versions of a given type of discrimination were run in each session. The sequence of conditions was counterbalanced across subjects and sessions.

The subject's task was to identify which of the two alternative stimuli was presented on each trial. The two alternatives appeared with equal probability. The subject initiated each trial by depressing two telegraph keys, the stimulus appeared .5 sec later, the response was made by releasing one of the two keys, and a bell was then rung if the response was correct. The left key was assigned to the shortest distance or duration in the univariate and equal-velocity bivariate conditions and to the slowest stimulus in the different-velocity bivariate condition. The subjects were informed as to which of the six conditions was operative during any given block of trials.

Each session consisted of two blocks of 230 trials: 30 practice trials followed immediately by 200 experimental trials. The two blocks were each devoted to a different version of the type of discrimination employed in that session. There was a short break between the two blocks of trials. A session required about 20 min. Each subject participated in three practice and six experimental sessions, which were devoted equally often to the three types of discriminations. The experimental data were thus based on 400 trials for each subject under each experimental condition.

Results

The results are presented in Tables 1 and 2. Table 1 gives the percentages of correct responses under each experimental condition. As may be seen, the most accurate

TABLE 2

Obtained and Predicted Discriminal Distances ($-ln\eta$) Between the Two Stimuli in Each Discrimination Condition of Experiment 1

	Average obtained discriminal distances				Linear predictions of bivariate distances	
Subjects	Time	Space	Equal velocity	Different velocity	Perceptual independence	Correlated dimensions
DH	.68	.46	.19	1.56	.82	1.14
JH	.70	.46	.32	2.04	.83	1.14
SN	.74	.67	.73	1.74	1.00	1.20
HT	.97	.91	.47	2.18	1.33	1.82
JT	.96	.80	.51	1.97	1.24	1.68
MW	1.10	1.08	.90	2.26	1.54	1.98
M	.86	.73	.52	1.96	1.13	1.49

Note. See text for definitions of models.

discrimination occurred under the different-velocity bivariate condition and the poorest discrimination occurred under the equal-velocity bivariate condition. In order to determine how the performance in the bivariate conditions compares with the predictions of linear models for the integration of information about time and space, Table 2 presents these data in terms of the discriminal distance between the two stimuli in each condition, along with the predictions of the two models given in Equations 1 and 2 above. (The measure of discriminal distance is the measure $-ln\eta$ from Luce's choice theory. See Luce, 1963, and Footnote 2.)

The results in Table 2 show that performance in both of the bivariate conditions was incompatible with a linear model for the integration of spatial and temporal information. Performance in the different-velocity condition was consistently superior to the predictions not only of the perceptual independence model and of the more general correlated dimensions model, but was even greater than the *sum* of the discriminal distances on the spatial and temporal dimensions, which would represent an upper bound on the predictions from the class of linear models. The fact that performance in the equal-velocity condition was always below the performance in the different-velocity condition is also inconsistent with the hypothesis that discrimination in these bivariate conditions was determined solely by the discriminations of the component spatial and temporal variables. Perceptual information was evidently provided by the specific combinations of the two component variables. Performance in the equal-velocity condition was also consistently below the prediction of the perceptual independence model, and for five of the six subjects it was even below the *minimum* discrimination on the two component dimensions which would represent a lower bound on the predictions of any reasonable linear integration model. With the exception of this last comparison, all of these departures of the observed values from the predicted values are statistically significant by a two-tailed sign test ($p <$ .05).

Discussion

The principal result of this experiment was that discriminations of the velocities of moving stimuli were too accurate to be attributed only to dicriminations of the spatial and temporal extents of the motion. The implication is that the perception of velocity need not be derived from prior discriminations of time and space. Spatial distance and temporal duration were the independent physical variables describing the stimuli from the experimenter's viewpoint, but these were not the only perceptually relevant variables from the subjects' viewpoint. Evidently, the *relation* between time and space was perceived in this experiment.

If time and space were perceptually related in the present experiment, they have apparently not always been so related in other experiments. Specifically, Mandriota et al. (1962) found that discriminations of spatial distance and temporal duration were both more accurate than "heterodimensional" discriminations that were supposedly based on velocity alone. One major difference in the two experiments concerns the physical properties of the stimuli varying in spatial distance. In the experiment of Mandriota et al. the initial position of the stimulus was apparently constant, permitting the subject to discriminate between the fixed-duration stimuli solely by their final positions. In the present experiment, however, both initial and final positions were randomly varied across trials, requiring that the spatial discriminations be based on the perceived distance between the initial and final positions. A second important difference in the experiments is that the heterodimensional condition in the Mandriota et al. experiment attempted to remove the component spatial and temporal cues from the velocity discriminations by making the velocity uncorrelated with either of the single variables; in contrast, we have examined the contribution of velocity by combining the spatial and temporal variables redundantly. Although a quantitative comparison of the two results cannot be made, Mandriota et al. seem to have succeeded in making their subjects less sensitive to velocity than to spatial extent, whereas we seem to have obtained the opposite result.

The results of the present experiment are, however, quite compatible with Mashour's (1964) findings with magnitude estimation that the psychophysical function for velocity grows more rapidly than that for either time or space.

Experiment 2

The purpose of this experiment was to discover whether the same perceptual relation between time and space that was found for continuous motion in Experiment 1 could also be found for apparent motion.

In some respects the result of Experiment 1 might not be surprising: The velocity of a continuously moving stimulus may be more discriminable than its spatial and temporal extents because the latter discriminations depend on knowledge of the initial and final positions of the stimulus, whereas the velocity is defined between any two successive positions. There is more available physical information about velocity than about spatial or temporal extent. A subject might blink and completely miss the onset of the stimulus and thus have no knowledge of its spatial or temporal extents, but could still be able to determine its velocity by its motion between other positions. The phenomenon of *apparent* motion, however, might be functionally different. Since the stimulus physically occurs at only the initial and final positions, its "velocity" is determined by the same events that determine its spatial and temporal extents; its "motion" is only in the eye of its beholder. Even if such a discrete stimulus appears to move, knowledge of its motion might be completely determined by knowledge of its spatial and temporal positions.

Two relevant studies of apparent motion have, however, offered different answers to this question. Kinchla and Allan (1969) found that the detection of motion could be quantitatively well described as a spatial discrimination of initial and final positions. The interstimulus intervals employed by Kinchla and Allan were relatively long (more than .5 sec), and this may have diminished the visual interactions between the two flashes. Ratings of the subjective quality of apparent motion are typically lower at intervals of .5 sec than at intervals around 50 to 100 msec (Kahneman & Wolman, 1970; Kolers, 1972). Another experiment suggesting that different processes may control apparent motion at shorter interstimulus intervals was conducted by Biederman-Thorson et al. (1971), who demonstrated that spatial discriminations were more accurate for successive than for simultaneously presented stimuli. At interstimulus intervals in the range of about 2 to 100 msec, observers were able to identify the direction of motion between two spatial positions that could not be discriminated from a stimulus at a single spatial position when the interstimulus interval was outside this range. Neither of these two experiments, however, was directly concerned with discriminations of velocity per se.

There were two basic modifications in the design of Experiment 2 from that of Experiment 1: (a) Each stimulus consisted of two successive spots of light, producing apparent rather than continuous motion. (b) There were two stimulus sets, one with relatively short interstimulus intervals yielding subjectively good apparent motion and the other with relatively long interstimulus intervals yielding subjectively poor apparent motion.

Method

Stimuli. The stimuli were displayed and controlled with essentially the same equipment and viewing conditions as in Experiment 1. The only important change was in the specific cathode-ray tube display scope: Due to an electronic problem with the scope used in the first experiment, it was necessary to substitute an otherwise identical scope with a slower phosphor (P-31, which decays to .1% luminance in 32 msec). Observations of these stimuli displayed on both scopes revealed no discernible difference in the two displays. In any case, no information logically relevant to the subject's task was associated with this stimulus characteristic. Kahneman and Wolman (1970) have shown that for onset asynchronies below 100 msec the stimulus duration has no effect on the subjective quality of apparent motion.

The general design of the stimulus set was the same as in Experiment 1. In this case, though, each stimulus consisted of two successive spots separated by a variable spatial distance and temporal interval. The spatial separation was either 50 or 65 units of the 512 possible display locations across the horizontal axis of the scope; these corresponded to about 23 and 30 minutes of visual angle at the viewing distance used. The temporal interstimulus interval was either 50 or 65 msec in one set of stimuli and was either 500 or 650 msec in the other set. According to published literature (e.g., Kahneman and Wolman, 1970), the shorter intervals should yield a much more compelling appearance of motion than the longer intervals. The longer intervals were selected in part to be consistent with those employed by Kinchla and Allan (1969). Both the first and second light flashes were activated by 16 pulses from the computer, for a total duration of 90 microsec.

Subjects. Six students at Vanderbilt University served as paid volunteers. None had served in the first experiment. Five of the subjects were students in an undergraduate perception class and received course credit for participation.

Procedure. As in Experiment 1, there were six different discrimination conditions determined by the particular pair of stimulus alternatives that occurred in a block of trials. In this experiment there were two such sets of conditions, one in which the temporal intervals were short (50 and 65 msec) and another set in which the intervals were long (500 and 650 msec).

There were four blocks of 120 trials in each session. One block was assigned to the spatial discrimination (with either the shorter or longer of the two alternative time durations for a given set of stimuli), another block was assigned to the temporal discrimination (with either the shorter or longer of the two alternative spatial separations), another block to the equal-velocity bivariate discrimination, and the remaining block to the different-velocity bivariate discrimination. The subjects were informed as to which condition was operative during any block. The first 20 trials in each block were considered practice and were not counted.

Each subject served for 11 sessions. The first 6 sessions were devoted to either the short-interval or long-interval set of stimuli; the first two of these sessions were considered practice and were not counted. The last five sessions were devoted to the other of the two sets of stimuli; the first session in this group was counted as practice. Thus, there was a total of 400 trials for each subject for each of the four basic discrimination conditions with each of the two sets of stimuli. The ordering of the experimental conditions was counterbalanced over sessions and subjects.

Other aspects of the task and procedure were the same as in Experiment 1.

Results

The results are presented in Tables 3 and 4. Table 3 gives the percentages of correct responses under the four basic discrimination conditions (time, space, equal-velocity bivariate, and different-velocity bivariate) for each of the two sets of stimuli (short intervals versus long intervals). These data indicate that the relative discriminabilities of the various pairs of stimuli were dependent on whether the interstimulus intervals were short (50 and 65 msec) or long (500 and 650 msec). A more analytic view of these results is provided by Table 4, which gives the discriminal distance ($-ln\eta$) between the two stimuli in each condition and also gives the predictions of the perceptual independence model for the bivariate conditions. (The data in Table 4 are the average distance measures for the four sessions for each subject under each condition. The predictions are based on these averages rather than the average of the predictions in each session.) The predictions of the correlated dimensions model are not included in this table because on the average these predictions were almost

TABLE 3

PERCENTAGES OF CORRECT RESPONSES IN EACH DISCRIMINATION CONDITION OF EXPERIMENT 2

	Subjects						
Discrimination condition	WB	JG	NG	TH	BK	PP	*M*
Short intervals, good motion							
Univariate							
Time	59	52	60	54	58	56	56.5
Space	70	67	62	78	71	54	67.1
Bivariate							
Equal velocity	67	74	59	80	71	57	67.8
Different velocity	78	73	72	87	75	62	74.6
Long intervals, poor motion							
Univariate							
Time	80	62	91	52	93	50	71.4
Space	58	62	61	61	68	55	60.8
Bivariate							
Equal velocity	83	63	89	70	90	66	76.9
Different velocity	82	56	86	55	90	57	70.9

identical to those of the perceptual independence model for these data. In both the short- and long-interval conditions the obtained discriminal distances for the equal-velocity pair were close to the predictions of the perceptual independence model, with the result that the predictions given by Equations 1 and 2 for the different-velocity pair become equivalent.

The data in Table 4 reflect the following results: (a) With the short-interval set of stimuli (50 and 65 msec), discrimination of the different-velocity bivariate pair was better than that for the equal-velocity pair. This superiority was obtained in 18 of the 24 total sessions, which is statistically reliable by a two-tailed sign test ($p < .05$). (b) Discrimination of the different-velocity pair

TABLE 4

OBTAINED DISCRIMINAL DISTANCES ($-ln\eta$) FOR EACH DISCRIMINATION CONDITION AND THE PREDICTIONS OF THE PERCEPTUAL INDEPENDENCE MODEL FOR THE BIVARIATE CONDITIONS IN EXPERIMENT 2

	Subjects						
Discrimination condition	WB	JG	NG	TH	BK	PP	*M*
Short intervals, good motion							
Univariate							
Time	.38	.07	.47	.16	.34	.25	.28
Space	.90	.72	.51	1.35	.96	.17	.77
Bivariate							
Equal velocity	.71	1.13	.37	1.41	.97	.27	.81
Different velocity	1.28	1.04	.99	1.99	1.16	.60	1.18
Prediction of independence model	.98	.73	.70	1.36	1.02	.30	.85
Long intervals, poor motion							
Univariate							
Time	1.49	.52	2.72	.08	2.75	−.01	1.26
Space	.35	.50	.46	.47	.65	.20	.44
Bivariate							
Equal velocity	1.72	.56	2.31	.90	2.43	.68	1.43
Different velocity	1.79	.22	1.82	.19	2.55	.31	1.15
Prediction of independence model	1.53	.73	2.76	.47	2.83	.20	1.42

in this short-interval set was also better than predicted by the perceptual independence model. This superiority was obtained in 21 of the 24 sessions ($p < .001$, by a two-tailed sign test). (c) Discrimination of the equal-velocity pair in this set of stimuli was close to the predictions of the perceptual independence model. Accuracy was higher than predicted in 10 of the 24 sessions. (d) With the long-interval set of stimuli (500 and 650 msec), discrimination was better for the equal-velocity pair than for the different-velocity pair. This relationship occurred in 18 of the 24 sessions ($p < .05$). (e) Discrimination of the different-velocity pair in this set of stimuli was below the predictions of the perceptual independence model in 18 of the 24 sessions ($p < .05$). (f) Discrimination of the equal-velocity pair in this set was close to the predictions of the perceptual independence model (above in 12 sessions and below in 12 other sessions).

The poor discrimination between the different-velocity bivariate pair in the long-interval set of stimuli appears puzzling and deserves comment. A probable explanation is that the assignment of responses to stimuli was confusing in this condition. In the univariate conditions and in the equal-velocity condition the left response switch was always assigned to the stimulus with the smaller spatial and/or temporal distance between the two flashes and the right switch was always assigned to the stimulus with the larger value on either variable. But in the different-velocity bivariate condition, the shorter spatial distance was paired with the larger temporal duration, and the mapping of the temporal variable onto the responses was consequently the reverse of that for all other conditions. It seems likely that the performance with the different-velocity pair in both stimulus sets is artifactually suppressed by this arrangement.

Discussion

The finding of this experiment was that, when the temporal interval between spatially neighboring light flashes was short enough to permit a good subjective impression of apparent motion, then discriminations between stimuli with different "velocities" was too accurate to be attributed only to dicriminations of the spatial and temporal distances between the two successive light flashes. Some perceptual information about the speed of apparent motion was associated with the specific combinations of values of the spatial and temporal variables. Evidently, a perceptual relation between time and space was functional in this experiment, though the effect was not as large as with the continuously moving stimuli used in Experiment 1.

One difference in the results of the two experiments was that the discriminability of the equal-velocity bivariate stimuli in this experiment was close to what was predicted by the perceptual independence model, whereas with the continuously moving stimuli the discrimination was poor for this pair of stimuli. Subjects apparently discriminated between this pair of stimuli in terms of the component spatial and temporal variables, without interference from a perceptual relation between time and space as in Experiment 1. Subjects were apparently able to attend to different stimulus characteristics under various discrimination conditions.

The finding with the short-interval set of stimuli (50 and 65 msec) is compatible with the demonstration by Biederman-Thorson et al. (1971) that such temporal asynchronies can enhance discrimination of the spatial positions of adjacent stimuli.

The perceptual relation between time and space was found in the present experiment, however, to depend upon the temporal separation between the successive light flashes. When the interstimulus interval was .5 sec or more, no evidence of a perceptual relation between the component variables was obtained. This finding might account for the failure of Kinchla and Allan (1969) to obtain evidence for the role of velocity in the apparent motion of stimuli temporally separated by such amounts. Different perceptual processes seem to control the perception of motion at short and at long intervals.

GENERAL DISCUSSION

The question with which this study began was whether the discrimination of velocity

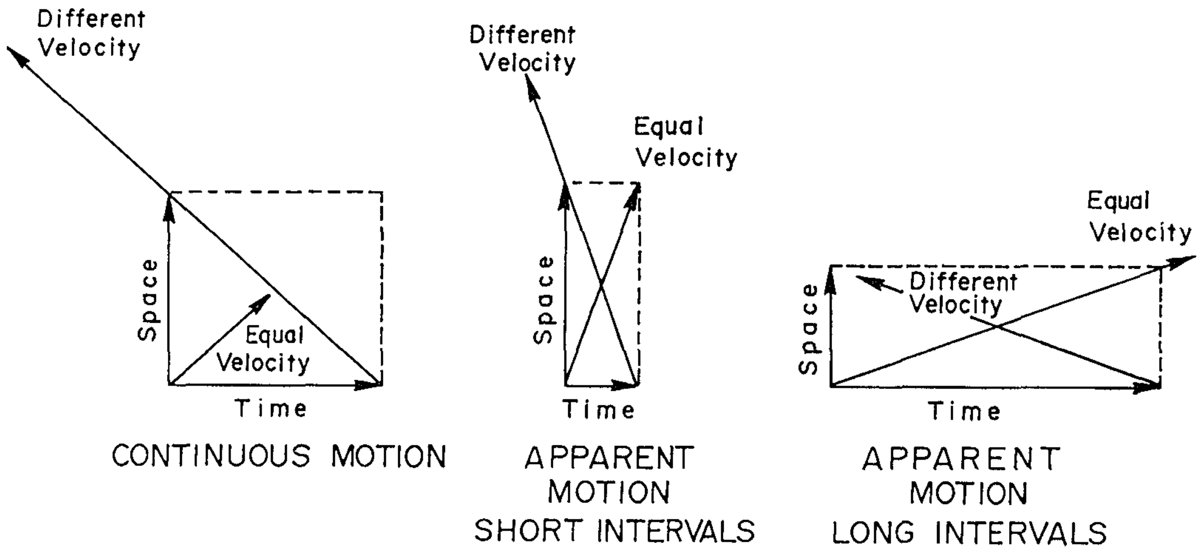

FIGURE 2. Vector-space descriptions of the results of both experiments. (The lengths of the vectors are proportional to the average discriminal distances obtained for each discrimination. The predictions of the perceptual independence model are indicated by the diagonal distance inside each rectangular space [though these are very slight underestimates of the averages of the predictions].)

is determined by discriminations of spatial and temporal extent. The answer provided by both experiments is no. Discriminations of velocity are evidently often based on visual information that derives from a relationship between the spatial and temporal extents of the motion. Velocity seems to be a directly perceived attribute of moving stimulation.

A general illustration of the results of these experiments is provided by Figure 2. The average discriminations between each of the four types of stimulus pairs (differing in temporal duration, spatial distance, both variables with equal velocity, and both variables with different velocities) are represented in terms of vector spaces, where the length of the vector is proportional to the discriminability of the corresponding pair of stimuli. The predictions of the perceptual independence model are indicated approximately by the diagonal distance between the spatial and temporal vectors. (These predictions are slight underestimates, since they are based on the average lengths of the time and space vectors. The prediction from the average is not equal to the average prediction.) The failure of the spatial and temporal discriminations to account for the discriminability of the bivariate pair with different velocities is described by the discrepancy between the length of the different-velocity vector and the length of the diagonal distance between the time and space vectors.

Perceptual relations among the individual values of ostensibly separate stimulus variables are likely to be important in many other situations. The perceptual advantage in utilizing such relationships derives from the well-known superiority of comparative judgments based on external standards in contrast to absolute judgments based on internally calibrated standards (Hake, Rodwan, & Weintraub, 1966; Weintraub, 1971). Considerable environmental information is available in the coherent relation among multiple physical variables, and observers generally use this information (Gibson, 1966). In the case of moving objects, the invariance or coherence is defined on the relation between the spatial and temporal changes rather than on the discrete spatial and temporal positions. In most previous demonstrations of nonlinear perceptual relations among component stimulus variables (e.g., Lappin, 1971; Pomerantz & Garner, 1973; Weintraub, 1971), the relationships involved a single physical variable, which was usually spatial. It is noteworthy that the perceptually effective relationship in the present study was defined on two different physical dimensions.

REFERENCES

Bell, H. H., & Lappin, J. S. Sufficient conditions for the discrimination of motion. *Perception & Psychophysics,* 1973, *14,* 45–50.

Biederman-Thorson, M., Thorson, J., & Lange, G. D. Apparent movement due to closely spaced sequentially flashed dots in the human peripheral field of vision. *Vision Research,* 1971, *11,* 889–903.

Boring, E. G. *Sensation and perception in the history of experimental psychology.* New York: Appleton-Century-Crofts, 1942.

Brown, R. H. Velocity discrimination and the intensity-time relation. *Journal of the Optical Society of America,* 1955, *45,* 189–192.

Garner, W. R. Information integration and form of encoding. In A. W. Melton & E. Martin (Eds.), *Coding processes in human memory.* Washington, D.C.: V. H. Winston, 1972.

Gibson, J. J. Research on the visual perception of motion and change. In I. M. Spigel (Ed.), *Readings in the study of visually perceived movement.* New York: Harper & Row, 1965.

Gibson, J. J. *The senses considered as perceptual systems.* Boston: Houghton Mifflin, 1966.

Hake, H. W., Rodwan, A., & Weintraub, D. Noise reduction in perception. In K. R. Hammond (Ed.), *The psychology of Egon Brunswik.* New York: Holt, Rinehart & Winston, 1966.

Kahneman, L., & Wolman, R. E. Stroboscopic motion: Effects of duration and interval. *Perception & Psychophysics,* 1970, *8,* 161-164.

Kinchla, R. A., & Allan, L. G. A theory of visual movement perception. *Psychological Review,* 1969, *76,* 537-558.

Kolers, P. A. *Aspects of motion perception.* New York: Pergamon Press, 1972.

Lappin, J. S. Transformation-invariant cues in the recognition of simple visual patterns. *Perception & Psychophysics,* 1971, *10,* 367–370.

Leibowitz, H. W. Effect of reference lines on the discrimination of movement. *Journal of the Optical Society of America,* 1955, *45,* 829–830. (a)

Leibowitz, H. W., The relation between the rate threshold for the perception of movement and luminance for various durations of exposure. *Journal of Experimental Psychology,* 1955, *49,* 209-214. (b)

Luce, R. D. Detection and recognition. In R. D. Luce, R. Bush, & E. Galanter (Eds.), *Handbook of mathematical psychology* (Vol. 1). New York: Wiley, 1963.

Mandriota, F. J., Mintz, D. E., & Notterman, J. M. Visual velocity discrimination: Effects of spatial and temporal cues. *Science,* 1962, *138,* 437–438.

Mashour, M. *Psychophysical relations in the perception of velocity.* Stockholm, Sweden: Almqvist & Wiksell, 1964.

Pantle, A. J., & Sekuler, R. W. Velocity-sensitive elements in human vision: Initial psychophysical evidence. *Vision Research,* 1968, *8,* 445–450.

Pomerantz, J. R., & Garner, W. R. Stimulus configuration in selective attention tasks. *Perception & Psychophysics,* 1973, *14,* 565-569.

Sekuler, R. W., & Pantle, A. J. A model for after effects of seen movement. *Vision Research,* 1967, *7,* 427-439.

Weintraub, D. J. Rectangle discriminability: Perceptual relativity and the law of prägnanz. *Journal of Experimental Psychology,* 1971, *88,* 1–11.

Wertheimer, M. Experimentelle Studien über das Sehen von Bewegung. Translated in part in R. J. Herrnstein and E. G. Boring (Eds.), *A sourcebook in the history of psychology.* Cambridge, Mass.: Harvard University Press, 1966.

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