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# Perceived distance and the perceived speed of self-motion: Linear vs. angular velocity?

EUGENE R. WIST, H. C. DIENER, J. DICHGANS, and Th. BRANDT
*Neurologische Universitätsklinik mit Abteilung für Neurophysiologie, Freiburg i. Br., West Germany*

Experiments are reported in which it was found that, with the angular speed of a visual surround held constant, the perceived speed of rotary self-motion increased linearly with increasing perceived distance of this surround. This finding was in agreement with a motion constancy equation derived from a consideration of object-referred motion perception. Since information concerning distance is necessary for the perception of linear but not angular speed, this finding supports the conclusion that visually perceived rotary self-motion perception is dependent upon perceived linear surround motion at least in the horizontal plane. The visual motion constancy mechanism which operates for object-referred motion can apparently not be switched off for the special case of self-motion perception.

Subjective velocity of *object-referred motion* has been observed to exhibit *constancy* in structured visual environments. That is, although an object moving across the visual field at a constant physical speed decreases in angular speed as its plane of motion increases in physical distance, its perceived speed, nonetheless, remains relatively constant. Brown (1931) studied this phenomenon experimentally and found only a 20% diminution in the perceived speed of a stimulus moving in the frontoparallel plane when its physical distance was increased from 1 to 10 m (causing a 90% diminution of actual angular speed).

Although Brown failed to do so, Wallach (1939) has pointed out that these results are consistent with the *transposition principle* postulated by Brown (1931). According to this principle, the apparent speed of a moving stimulus will remain unaltered, if when its physical dimensions and those of its surround are decreased by a given proportion, its physical speed is decreased by the same proportion. Since all the dimensions of the moving stimulus (including its angular speed) are reduced proportionally with increasing distance, Wallach (1939) argued that no distance information was necessary for motion constancy.

The present investigation was undertaken in order to determine whether, in addition to the transposition principle, another motion constancy mechanism involving distance information plays a role in motion constancy. It has been demonstrated that distance information is at least sufficient for producing size constancy (Kilpatrick and Ittleson, 1953). It is proposed that just as the decrease in angular size of an object with increasing physical distance is compensated by a corresponding increase in perceived distance, the decrease in angular *speed* of an object with increasing physical distance is similarly compensated.

A consequence of this analysis was used to test its validity: if only the perceived distance of an object moving at a constant angular speed increases, then the perceived speed of that object should also increase. This is so because, in this case, the increase in perceived distance is not compensated by a corresponding decrease in angular speed, as would be the case in a normal environment.

These relationships are more evident in the proposed *motion constancy equation* below, which is based on a restatement of the size-distance invariance hypothesis that has been applied to size constancy (Gogel, Wist, & Harker, 1963; Kilpatrick & Ittleson, 1953):

$$M' = k\omega D'$$

where $k$ = a constant of proportionality, $\omega$ = the angular speed of the stimulus, $D'$ = the perceived distance of the stimulus in relation to the observer, and $M'$ = the perceived speed. The above relations expressed in the form of this equation indicate that if $D'$ increases while $\omega$ is held constant, then $M'$ must increase.

The Brown (1931) results described earlier are consistent with this equation as well as with the transposition principle. They represent the special case where angular speed ($\omega$) decreases as perceived distance ($D'$) increases. In experiments to be reported elsewhere, we verified that for *object-referred* motion perception (i.e., perceived motion of the environment or portions thereof with respect to the stationary

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observer), the relations expressed in the equation are valid when D′ is varied (Wist, Diener, & Dichgans, Note 1). In the experiments to be reported here, however, we were interested in rotary *self-referred* motion perception (i.e., perceived motion of self with respect to an apparently stationary environment) in order to determine whether the motion constancy mechanism would operate in this case as well, where it would seem to be both inappropriate and unnecessary.

Circularvection, in which a rotation of the entire visual field or a substantial portion thereof is perceived as pure self-rotation with respect to a seemingly stationary surround, was chosen for investigation. This movement illusion, first described by Helmholtz (1867) and later by Mach (1885), was studied under laboratory conditions by Fischer and Kornmüller (1930). Recent investigations have determined some of its physiological stimulus characteristics, have indicated its functional importance, and have shown that the neurophysiological basis of visually induced self-motion is a visual-vestibular convergence (Brandt, Dichgans, & Koenig, 1973; Brandt, Wist, & Dichgans, 1971; Dichgans, Schmidt, & Graf, 1973). It was shown that visually induced self-motion is not merely an illusion, but rather, a precondition for accurate self-motion perception, especially in the case of constant-velocity body motion when the vestibular receptors are not excited.

The purpose of the present study, then, was to determine to what extent motion constancy holds for the case of rotary self-referred motion, where its functional significance is not presently evident. It would seem that the *angular* speed of surround movement alone would be sufficient for the perception of angular self-rotary motion. The problem becomes apparent when it is noted that motion constancy as derived for object-referred motion implies that *linear* rather than angular motion is perceived. Thus, if linear motion perception is involved in self-referred motion as well, then with angular speed held constant, the perceived speed of self-rotation should decrease with a decrease in perceived distance. Preliminary observations confirmed this expectation, in that a decrease in D′ produced by fusional convergence reduced the perceived speed of circularvection consistent with the equation. Since fusional convergence results only in *reductions* of D′, it was not employed as the primary means of varying D′ in the present study. Instead, advantage was taken of the Pulfrich stereo effect (Pulfrich, 1922), which allowed increases as well as reductions in D′ without affecting either the accommodation or the convergence of the eyes.

## METHOD

### Subjects

Eleven university students (aged 19 to 27 years), naive concerning the phenomenon being investigated, were paid for their participation.

### Apparatus

The subject sat in an upholstered chair fitted with a head support so that the distance of his eyes from the cylindrical screen in Figure 1 was equal to its radius of curvature (79.5 cm). A Tönnies optokinetic stimulator was used to project a regular pattern of black and white stripes onto the screen. Relevant angular dimensions are given in Figure 1. The luminance of the dark stripes was 0.85 mL, while that of the white background was 5.85 mL. A small black disk, 1 deg in diam, affixed to the screen in the subject's median plane at eye lvel, served as the fixation point.

### Procedure

**Variation of perceived distance by means of the Pulfrich effect.** As is well known from the work of Lit (1949) and Pulfrich (1922), the magnitude of the change in perceived depth is a function of both

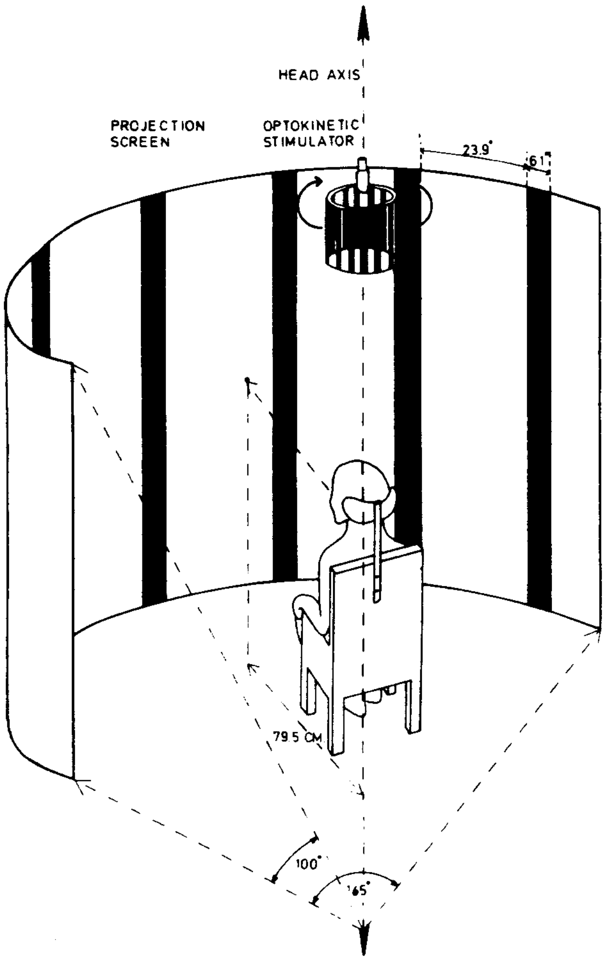


**Figure 1. Stimulus display with relevant dimensions. The dark point in the subject's median plane represents the fixation point.**

filter density (attenuation of luminance in one eye) and stimulus speed. The perceived relative distance between a unidirectionally moving horizontal stimulus and stationary contours in the visual field is increased when this stimulus is viewed with the filter covering one eye. When stimulus motion is toward the filter-covered eye, the moving stimulus appears closer than the stationary contours. The reverse is true for stimulus motion in the opposite direction. Thus, both the perceived relative depth between the moving stimulus and the stationary contours in the field and the perceived absolute distance of the moving stimulus from the subject are simultaneously affected by viewing through the filter. A preliminary experiment was necessary in order to choose filter densities and stimulus speeds such that an appropriate variation in the perceived distance of the moving stripes could be realized. On the basis of the results of this experiment, *two filter densities* (1.0 and 1.5 log units of attenuation) and *two stripe speeds* (80) and 130 deg/sec) were chosen which would produce two discriminably different distances of the apparent plane of motion in front of, and two behind, the plane of the projection screen. Stationary contours were provided by the small fixation disk affixed to the screen, as well as by the borders of the stimulus field.

**Magnitude estimations of perceived distance and self-motion velocity.** By means of the magnitude estimation technique of Stevens (1957), the perceived distance of the moving stripes and the subjective speed of self-motion was determined under eight randomly presented treatment combinations. These consisted of two filter-stimulus speed combinations (1.0 log unit filter with 80 deg/sec and 1.5 log unit filter with 130 deg/sec), with the filters covering either the left or the right eye and the stripes moving horizontally either to the left or to the right. For six subjects, each of the eight conditions was presented twice. Since no significant differences were found between first and second judgments for these subjects, the remaining five received only one trial per condition.

All estimations were made while fixation was maintained on a point located straight ahead in the plane of the projection screen (Figure 1). The subjects wore headphones through which either white noise or music was played in order to mask the motor noise of the stripe projector. A rest pause of 5-10 min was given halfway through the 50-min experimental session.

Two standard stimulus situations were presented which served as moduli with an arbitrary value of 100 for both perceived distance and perceived velocity of self-motion: one consisted of the stripes moving at 80 deg/sec, the other of the stripes moving at 130 deg/sec. The standard stimulus was viewed through a control filter (0.2 log attenuation) whose density was such as not to alter perceived distance. The fact that the modulus had the value "100" for both the 80- and 120-deg/sec stimulus speeds was not found confusing by the subjects, since the modulus condition was presented just prior to each magnitude estimation. Thus, the perceived speed associated with each modulus condition had to be retained for only several seconds prior to the making of each magnitude estimation. Except for two subjects, all judgments of distance and self-motion speed were made during a single stimulus presentation, with the former preceding the latter. For these two subjects, distance and velocity estimations were separated in time in order to test for a possible interaction between velocity and distance judgments. For all subjects, estimations of perceived distance were made only during stable circularvection, i.e., steady state self-referred rotary motion perception.

Upon exposure to a given optokinetic stimulus, the subjects typically experienced object-referred motion for several seconds, followed by a brief period in which a mixture of self- and object-referred motion existed. Under the conditions of the present experiment, the subjects experienced a pure self-referred motion after about 5 sec. It was just after this point in time that they made their magnitude estimates. Although some subjects may experience dizziness and slight nausea under these stimulus conditions, this was not true of the present subjects. Visual aftereffects were prevented by the relatively short exposure times and the rest intervals between trials. Optokinetic nystagmus was prevented by continuous fixation on the black disk affixed to the screen.

It should be stressed that for the stimulus conditions described above *only perceived distance was varied* for a given standard by changing the filter/eye/direction combination while the *angular speed of the moving pattern was held constant.*

## RESULTS

### Perceived Distance as a Function of Direction and Speed of Stripe Movement and Filter Density

As expected on the basis of the results of the preliminary experiment, and consistent with the results of Lit (1949) and Pulfrich (1922), the perceived distance of the moving stripes varied systematically as a function of stimulus speed, filter density, and movement direction. The quantitative data obtained from the scaling of perceived distance are presented in the fourth column of the table. Since no differences were found between corresponding depth locations produced by conditions in which the moving stripes were viewed with the filter over the left vs. right eye, these data were pooled for the calculation of the mean values. As can be seen, the deviation of perceived distance from the modulus condition (100, with the stripes moving in the plane of the screen) is symmetrical; that is, the mean value of 64.33 (apparent forward shift) is about 37% less than the modulus value, while the mean value of 136.94 (apparent rearward shift) is about 37% greater than this value. In both instances, the angular speed was unaltered at 130 deg/sec (Column 3). A corresponding effect was obtained for the 80-deg/sec stimulus speed. Here the deviation from the modulus condition was about 20% in each direction. t tests for related measures indicated that all distance estimation means differed significantly from each other ($p < .01$).

**Table 1**
**Mean Magnitude Estimations of Perceived Distance and Velocity of Circularvection***

| N† | Filter: Log Attenuation | Stripe Speed: Deg Per Sec | Perceived Distance: Mean | Perceived Distance: SD | Perceived CV Velocity: Mean | Perceived CV Velocity: SD |
|---|---|---|---|---|---|---|
| 36 | 1.5 | 130 | 64.33 | 11.25 | 69.94 | 15.95 |
| 32 | 1.0 | 80 | 81.46 | 7.39 | 78.25 | 12.55 |
| 32 | 1.0 | 80 | 120.47 | 9.55 | 120.00 | 11.18 |
| 36 | 1.5 | 130 | 136.94 | 20.01 | 125.97 | 12.01 |
| 136 | | | | | | |

**Modulus for perceived distance and CV velocity = 100. In the first two rows, the stripes moved in the direction* toward, *while in the last two rows they moved* away *from the filter-covered eye.*

*†N = total number of scores entering into each mean and SD. The Ns of 36 each were constituted as follows: 7 subjects completed all four conditions, while 4 completed two conditions (7 × 4 + 4 × 2 = 36). The Ns of 32 each resulted from the fact that Subject J.T. (see Figure 2) did not receive these conditions. The total N of 136 is equal to the number of data points in Figure 2.*

**Perceived Velocity or Rotary Self-Motion as a Function of Perceived Distance**

Changes in the perceived velocity of self-rotation during optokinetic stimulation were consistently related to changes in perceived distance. As can be seen in the sixth column of the table, perceived CV velocity increased with increased perceived distance. For the most potent stimulus-speed/filter combination, the mean deviation of CV velocity from the modulus condition was 27.5%, while for the less potent combination it was about 20%. Just as for the perceived distance estimates, t tests for related measures indicated that all velocity estimations differed significantly from each other ($p < .01$).

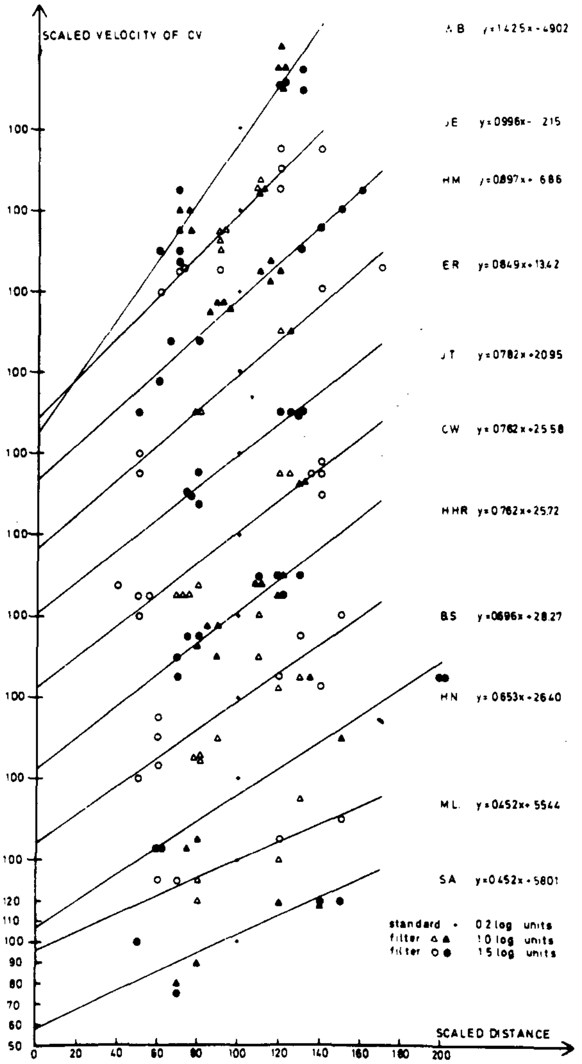


**Figure 2. Scaled velocity of circularvection (CV) as a function of the scaled (perceived) distance of the plane of the moving stripes from the subject. The individual functions for the 11 subjects are shown displaced vertically on the ordinate for clarity. The equations for the lines of best fit through the data points are given at the right for each subject.**

Individual data showing the relationship between scaled distance and scaled velocity of CV are shown in Figure 2. The means are arranged in order of increasing perceived distance on the abscissa, while corresponding CV speed estimates are plotted on the ordinate. The separate functions are displaced vertically on the ordinate for clarity. The equation describing the linear line of best fit for each subject is shown just to the right of each function. It can be seen that the slopes (k) of these functions representing the individual ks for the motion constancy equation vary between a minimum of 0.452 and a maximum of 1.425. Their mean is 0.79. While the interindividual differences in the slopes of these functions are large, differences in the amount of deviation of data points from the lines of best fit are small in comparison. The proportion of the variance of CV speed estimates accounted for by perceived distance was large. Mean $r^2$ for the 11 functions of Figure 2 was 0.862 ($SD = 0.099$). The lowest $r^2$ was 0.686, while the highest was 0.978. The median $r^2$ was 0.904.

The functions labeled H.N. and M.L. are those obtained from the two control subjects who made their magnitude estimations of perceived distance and CV velocity separately. Their functions are within the range of those obtained for the other subjects.

**Influence of Fusional and Accommodative Convergence on the Perceived Velocity of Rotary Self-Motion**

In order to demonstrate that the effect of perceived distance on the perceived velocity of self-motion is not restricted to the use of the Pulfrich phenomenon, supplementary investigations not described in the method section were carried out. In these experiments, fusional and accommodative convergence were used to produce alterations in perceived distance of the black and white striped inner walls of a revolving closed cylindrical drum described elsewhere (Brandt, Wist, & Dichgans, 1971). A change in the perceived distance of the moving stripes on the inside wall of the cylinder 75 cm from the eyes was now produced by having subjects fixate a point 20 cm from the eyes. As a result of fusional convergence, the apparent distance of the stripes shifted to approximately the distance of this fixation point. At the same time, for four subjects tested, the speed of CV decreased to 49% of that experienced when the fixation point was at the actual plane of motion of the stripes. Similarly, when the perceived distance of the stripes was reduced through the placement of either 6 or 12 diopter base-out prisms before the eyes, the apparent speed of CV was reduced by 14% and 32%, respectively. This manipulation of D′ by means of fusional and accommodative convergence left the angular speed of the retinal stimulus unaltered as in the previous experiment.

## DISCUSSION

When a visual surround is rotated about the observer at a constant angular speed, thus inducing an apparent self-rotation of the observer, the apparent distance of this surround can be altered by means of the Pulfrich effect, accommodative and fusional convergence. Although the angular velocity of the projected image across the retina is unaltered, the perceived velocity of self-motion is altered proportional to the shift in apparent distance. Thus, paradoxically, it is not the angular speed of environmental motion which determines the speed of rotary self-motion, but, rather, its *linear* speed.[1] Linear speed, however, can be involved only if motion constancy operates in this situation. On the basis of our results, we can conclude that distance information is at least one of the possible bases for motion constancy and probably is the only basis available in our experiments.

Our findings cannot readily be interpreted in terms of Brown's (1931) transposition principle, which at that time was derived from and applied to the case of object-referred motion. This principle implies that if all the dimensions of a motion field are reduced without at the same time reducing the linear speed of stimulus motion by the same proportion, then the apparent speed of motion will increase. In the present study, investigating the subjective velocity of rotary self-motion, just the opposite occurred. Both fusional and accommodative convergence left the actual angular and linear velocity unaltered and resulted in a perceived reduction in all dimensions of the moving field, but instead of an increase, a reduction in the perceived speed of self-motion was obtained, produced by the concurrent reduction in perceived distance.

In the main experiment, where the perceived distance of the moving stripes was altered by means of the Pulfrich effect, the situation was different because of the exclusive influence of the filters on the moving contours. Here, not all dimensions were equally affected by the filters: only the moving stripes were altered in perceived dimensions, appearing narrower at near perceived distances and wider at farther perceived distances. The apparent size of the large stationary field (the edges of the screen) through which they moved remained constant. Brown (1931) found that when the dimensions of the moving stimuli (and therefore their perceived sizes) were varied while holding field size constant, larger moving stimuli had smaller apparent speeds. The opposite was found in this study: the stripes appeared larger at the farther perceived distances, but, as can be seen from Figure 2, the corresponding CV speeds were greater rather than smaller.

The results are consistent with the proposed motion constancy equation, and the rather large k values indicate the operation of a quite powerful constancy mechanism for self-referred motion perception. Unfortunately, object-referred motion perception could not be studied under identical stimulus conditions, since after a very short latency, the illusion of CV was inescapably forced upon the subjects. This latency was too short to allow the measurement of either perceived distance or the perceived speed of object-referred motion.

It should be noted that in the present experiment the angular *size* as well as the angular speed of the moving stripes was held constant. Under natural conditions, however, although their physical sizes would remain constant, the angular sizes of the objects in a moving surround would decrease proportionally with increasing distance from the observer. Therefore, the question arises as to whether the relationship between D′ and CV speed shown in Figure 2 still holds when the angular size of the stripes decreases with increasing D′ (i.e., when their physical size is held constant). This condition was tested in a supplementary experiment in which, for a constant angular speed, the physical distance of the moving stripes was varied (and therefore their linear speed) while holding their physical size constant. The same increase in CV speed with increased D′ was observed. Therefore, the proposed motion constancy equation appears to hold whether the angular or the physical size of the moving stimulus pattern is held constant. Distance information, therefore, can affect the speed of apparent self-motion under a condition approximating that of a real environment (physical size constant) as well as under the less natural condition in which angular size is held constant.

The existence of a motion constancy mechanism for object-referred motion is biologically adaptive as well as consistent with the existence of size constancy (Rock, Hill, & Fineman, 1968). It is not, however, obviously necessary for the organism to have information about linear speed when the perception of self-rotary motion is involved. Rather, information concerning the angular speed of environmental motion which normally occurs in the direction opposite to that of body motion would seem both more consistent and compatible with the perception of angular motion of the body about the earth's axis. However, the data suggest that the motion constancy mechanism operating for object-referred motion perception cannot be turned off for the special case of rotary self-referred motion perception. This interpretation possibly provides a hint as to the still unknown pathway through which visual motion information converges onto the vestibular nuclei (Dichgans & Brandt, 1972; Dichgans, Schmidt, &

Graf, 1973; Henn, Young, & Finley, 1973). Motion constancy information would presumably be processed in the visual cortex prior to a descending pathway to the vestibular nuclei. Finally, it should be noted that for oculomotor purposes, the visual system can operate without a motion constancy mechanism. We have observed that slow-phase velocity of optokinetic nystagmus is independent of the perceived distance of the horizontally moving optokinetic stimulus.

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## NOTE

1. In a quite different context, an unexpected relationship between angular stimulus motion and the perception of linear motion has also been found. Both Gogel and Tietz (1974) and Hay and Sawyer (1969) found that the amount of absolute motion parallax produced by movements of the head from side to side in the dark is a function of the perceived distance of the point of light viewed during such movements. When, for example, the perceived distance of the light point is reduced by viewing through base-out prisms which increase the convergence of the eyes, the amount of perceived motion parallax of the point is reduced (Hay & Sawyer, 1969). Yet, if information concerning the angular shift in the spatial location of the point during head movements was involved, no change in the amount of parallax ought to have been found as a function of convergence. These results indicate that the perception of a linear rather than of an angular shift in spatial location occurs in absolute motion parallax.

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