Reports

Distortions of Apparent Velocity: A New Optical Illusion

Abstract. *To an observer whose one eye is covered with a relatively strong filter (approximately 90 percent extinction) and who views a landscape from the side window of a moving automobile, the velocity of the vehicle appears to be markedly reduced when the uncovered eye is in the forward or leading position (in the sense of motion of the vehicle); the velocity seems to be increased when the covered eye is in the leading position. The illusion of reduced velocity is accompanied by an apparent dwarfing of objects near the roadside and an apparent foreshortening of the distance between object and observer; the illusion of increased velocity is accompanied by an apparent increase in size of objects and an increase in their apparent distance. These illusions can be understood as corollaries of the well-known Pulfrich phenomenon.*

The Pulfrich pendulum is one of the most spectacular optical illusions that can be demonstrated in the laboratory. When a pendulum is swung in a frontal plane before an observer who is viewing binocularly with a relatively strong filter (about 75 to 95 percent extinction) over one eye, the path traversed by the bob appears to be an ellipse that involves major displacement toward and away from the observer. If, for example, the right eye is darkened by the filter, the bob will appear to the observer to move closer to him as it moves from left to right and will appear to move farther away as it moves from right to left. The first quantitative studies of this illusion were undertaken by Pulfrich (*1*), and the subsequent literature on the subject is voluminous (*2–7*). The generally accepted explanation for the phenomenon (Fig. 1) invokes a greater latency for vision under reduced illumination, with the result that the darkened eye perceives the bob at a point in space which it occupied several milliseconds previous to the time at which it is perceived by the undarkened eye. The illusion is apparently not related to ocular convergence (Fig. 1A) but, instead, to stereoscopy (Fig. 1B), since it disappears when the pendulum is the only object in the field of view (*2*, *3*); it persists even when the observer fixates on an object well outside the plane of oscillation of the pendulum (*3*, *4*); and it is clearly noticeable—even more pronounced—at distances of up to 40 m (*5*), far beyond the limits of useful convergence information.

An even more dramatic demonstration of the Pulfrich phenomenon can be obtained if the pendulum bob swings in a plane slightly in front of the observer but greatly beneath his eye level: the suspending cord or rod will appear to lengthen and shorten like a strip of rubber (*8*). This manifestation follows logically, of course, from the analysis of Fig. 1; it is, however, more disconcerting to the observer than when the pendulum is at eye level, because the vertical motion implies an impossible elasticity of the supporting cord or rod rather than an elliptical path, which is a false but logically acceptable phenomenon.

It is the purpose of this report to describe a new optical illusion: a distortion of the apparent velocity for an observer who is in a moving vehicle and who has one eye covered with a filter. A careful consideration shows that this illusion is probably also a manifestation of the Pulfrich phenomenon but in a different context.

The apparent velocity illusion was first noticed (*8*) by an observer who was looking out the side window of an automobile that was moving at a steady speed of about 80 km/hr. The observer wore a pair of inexpensive sunglasses (93 percent extinction) from which the left lens had been removed; the right lens was intact. During observation out the right side window, the speed of the vehicle was apparently much slower than during monocular observation with either eye (that is, with or without filter) or during binocular observation, whether with complete sunglasses or without any filter. Similar observation, still with the right eye covered by the filter, out the left side of the vehicle gave an impression of greater speed than actual. The effect was completely reciprocal: when the left eye was covered by the filter, observation out the left side of the automobile led to an illusion of reduced velocity, and the view from the right side led to an apparent increase in velocity.

When the illusion of reduced velocity is observed, there seems to be a miniaturization or dwarfing of objects of known size, such as automobiles, humans, or domestic animals, which are within about 200 m of the roadside; viewed in the opposite direction, with apparently increased velocity, such nearby objects seem to assume larger-than-life dimensions. Particularly when objects of unknown dimensions are observed, such as trees or roadside signs, the apparently reduced velocity is accompanied by an apparent decrease in the distance of the object from the observer; an apparent increase in distance is usually noticeable under faster apparent motion. For the observer, the total effect of the increased velocity illusion is often tiring and may even be confusing, but the reduced velocity illusion resembles the effect of a moving stereoscope, with the environment seeming to float gently past the vehicle.

The intensity of the illusion was found to be inversely related to light intensity; thus it is least intense, or nonexistent, in full overhead sunlight on a bright day. A strong pattern of light and shadow, which emphasizes contours, seems to accentuate the illusion. At comparable light intensities, the illusion also seems to be more pronounced in a complex environment, where objects can be seen at several distances within 100 m of the roadside. A forested area can provide both complexity and a pattern of light and shadow, and such environments seem to be optimal for the illusion. Although the speed of the vehicle was found to influence the magnitude of the illusion, some effect has often been noted even at speeds of less than 40 km/hr. The effect is not dependent on any peculiarity of the sunglasses with which it was first observed; a gray neutral-density filter with 90 percent extinction (Kodak Wratten filter, N.D. 1.0) is entirely adequate to produce the phenomena described.

Under appropriate lighting conditions and vehicular velocity, the illusion of slowed motion has been reported by all observers tested. The illusion of apparently increased velocity was less reliably reported. Although there was general agreement that switching the filter from the following to the leading eye gave an impression of marked increase in apparent velocity, some subjects (at least initially) reported that the reversal of filter position simply destroyed the illusion of slowed motion rather than producing an illusion of velocity faster than actual.

If the accepted explanation of the Pulfrich pendulum illusion is transposed from the context of a fixed observer, fixed background, and object moving with sinusoidal velocities, to the context of a fixed environment and steadily moving observer, an adequate explanation of the total described illusion seems available. The greater latency of the darkened eye would result in its perception of the roadside environment from a position occupied by the observer some milliseconds before perception by the uncovered eye (see Fig. 2A). If the darkened eye is the following eye (in the sense of motion of the observer), the reconciliation of these views would correspond to a nearer position of the objects in the visual field (Fig. 2B); if it is the leading eye, the correspondence would be to a farther position. It may not, however, be immediately clear why the nearer object should be seen as closer, as indicated in Fig. 2B, rather than the farther object being seen as more distant; the latter interpretation (Fig. 2C) might seem to be an equally adequate reconciliation of the observed parallax. With the pendulum, such an alternative is ordinarily excluded (*9*) because of the fixed coordinate system, in which only the position of the moving pendulum permits uncertainty (Fig. 1B). A careful consideration of the geometry of the moving vehicle situation, however (Fig. 2, B and C), shows that (i) the apparent displacement of the closer object to a nearer position always involves a smaller transfer of position than the corresponding required displacement of the more distant object; (ii) for many configurations of two objects, even apparent displacement of the distant object to infinity would require some displacement of the near object toward a nearer position (Fig. 3A); and (iii) when several objects are present at different depths in the visual field, the far-object-fixed interpretation leads to a relatively coherent set of apparent distances, since the apparent distance of the near object is relatively stable over a wide range of possible locations of the far reference point (Fig. 3B); the near-object-fixed interpretation can yield radically different apparent distances for the far object, depending on the relationship between distances to near and far object (Fig. 3A). Hence, the illusion that the near objects are closer is the more acceptable—often [see (ii) above] the only available—interpretation of the visual field.

The apparent dwarfing of an observed human figure, automobile, or the like is a "reasonable" consequence of this distortion of apparent distance, since the actual vertical visual angle subtended by an observed figure corresponds to the real, greater distance; to reconcile this apparent size with apparent distance, a "dwarfing" is the only subjective interpretation available. An analog of this situation has been reported with the Pulfrich pendulum: when the pendulum bob is a sphere of appreciable size, the bob seems to shrink in diameter as its apparent elliptical motion approaches the observer, and it seems to become enlarged at the more distant apparent points (*5*).

The initially noted illusion of altered velocity also seems readily understandable in this context. For a moving observer an object at a given distance has an apparent angular velocity in a horizontal plane, and for a given real velocity there is a reciprocal relationship between distance and apparent angular velocity. If the object is perceived as being appreciably closer than its actual distance while keeping its "actual" horizontal angular velocity, the object would be expected to have an apparently reduced absolute velocity relative to the observer. In principle, of course, the same kind of a velocity illusion should be a component of the simple Pulfrich pendulum illusion, although it has apparently never been reported; that is, during the portion of the pendulum's apparently elliptical path when it seems nearer the observer, it should also seem to move at a slower absolute velocity than during the opposite limb of motion. It is not surprising, however, that this illusion has not been reported for the moving pendulum, because, since the bob is subject to continuous acceleration, the extreme velocities to be compared occur at opposite midpoints of the motion. For an observer in a steadily moving ve-

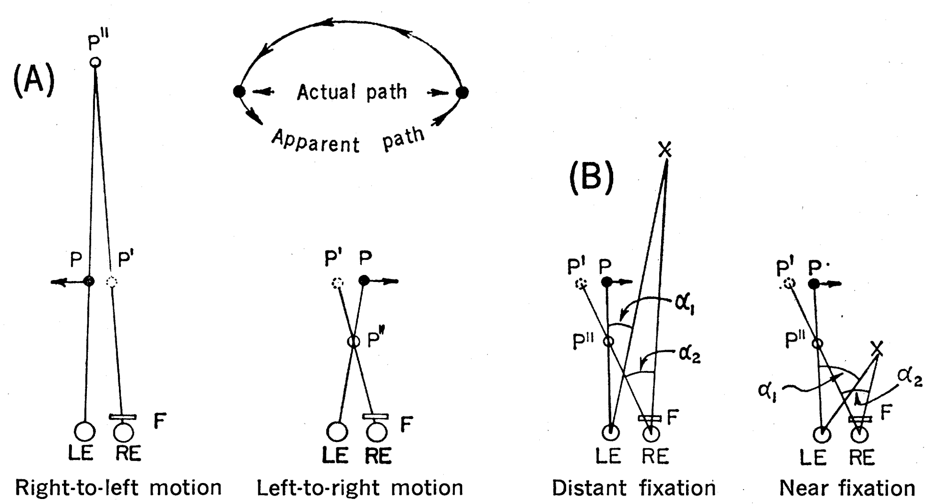


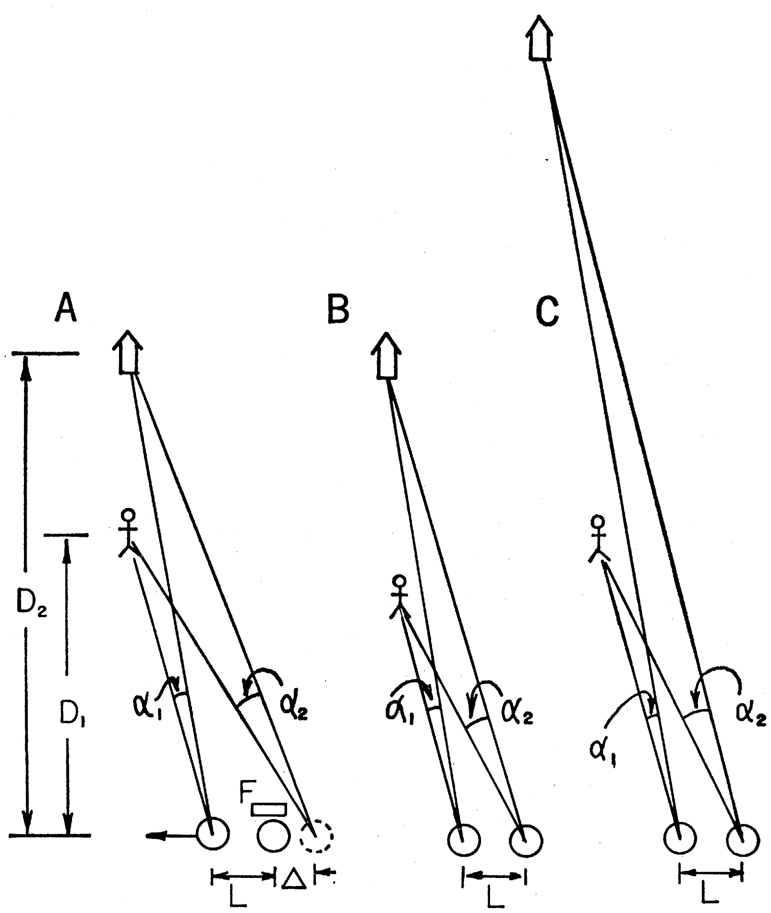
Fig. 1. (A) Plan view of the pendulum illusion. *LE* and *RE* are left and right eyes, respectively; *F*, filter; *P*, position of bob perceived by uncovered eye; *P'*, position perceived by covered eye at moment of perception by uncovered eye; *P''*, perceived image under binocular fusion. Schematic diagrams of this type appear in conjunction with nearly all discussions of the Pulfrich pendulum illusion. Such sketches could be taken to imply changes in ocular convergence as the mechanism of perceived distance. Hence, Fig. 1B is offered to emphasize that perceived distance is primarily a parallax phenomenon, although the implied magnitude of the illusion is identical with that of Fig. 1A. (B) Parallax interpretation of the pendulum illusion for left-to-right motion, right eye covered. *X*, fixation or reference point; α_1, α_2, visual angles subtended by distance between perceived position of pendulum bob and reference point for uncovered and covered eyes, respectively; *P''*, apparent position of bob, required to reconcile differences in visual angle as perceived by the two eyes; other symbols are as defined in Fig. 1A.

hicle, the apparent velocity component of the illusion is much easier to assess and is, in fact, usually initially more striking than the apparent distortions of size and distance.

The fact that the illusion is more pronounced in a complex landscape and scarcely noticeable over an open, level field is consistent with reports on the Pulfrich pendulum illusion, which is not noticeable unless objects other than the pendulum are in the visual field (*2*, *3*). The dependence of the illusion on overall illumination, with less distortion in full sunlight, corresponds with quantitative data on the Pulfrich pendulum illusion (*6*, *7*). The dependence of the illusion on vehicular velocity is, of course, compatible with an explanation based on the Pulfrich phenomenon but would probably also be a consequence of nearly any model proposed to account for the apparent velocity illusion.

At a velocity of 80 km/hr, a latency difference of 3 msec would serve approximately to double the effective interocular distance (*10*), when the uncovered eye is leading, and would correspond to an apparent halving of the distances to nearby objects (Fig. 3B) and, thus (perhaps), to a halving of apparent velocity. So large a latency difference would also serve, however, to reduce interocular distance to zero, when the covered eye is leading, and hence be expected to lead to a total loss of stereoscopy. The fact that an illusion of increased velocity is obtained when the covered eye is in a leading position—indeed, the simple fact that any "coherent" binocular vision is possible under these conditions—suggests that the actual difference in latency for the two eyes under the observational conditions described is somewhat less than 3 msec. Such a value would also be consistent with the subjective impression that the dwarfing of nearby objects, which accompanies the reduced velocity illusion, seldom seems to be by as much as a factor of 2 (Fig. 3B).

Extrapolation of laboratory data on the Pulfrich pendulum illusion (*11*) indicates that a latency difference of less than 3 msec should be expected only at light intensities between about 6,000 and 18,000 lux, when a 90 percent extinction filter is used. Although



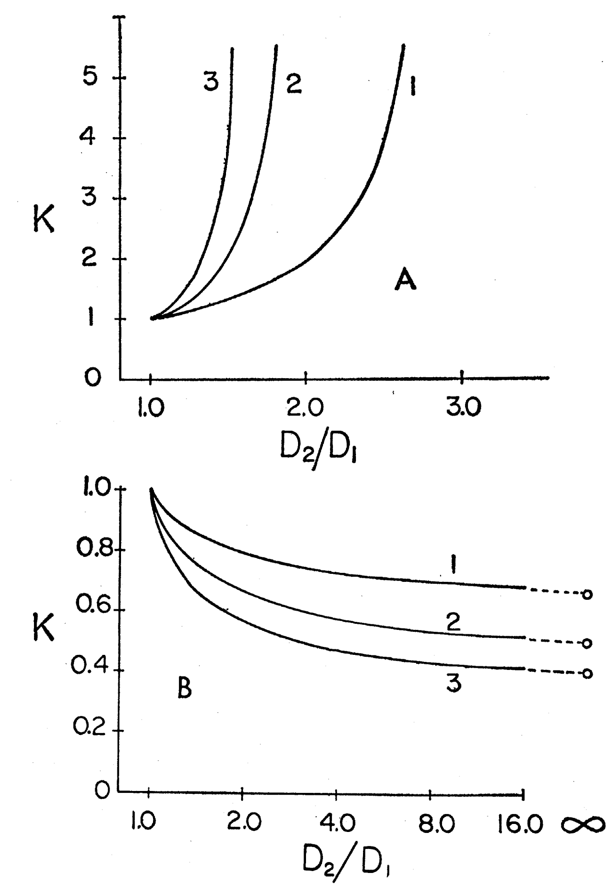


Fig. 2 (left). (A) Latency difference interpretation of the moving observer situation, observer moving from right to left. D_1 is distance to nearer of two objects; D_2, distance to farther or reference point; L, interocular distance; Δ, distance traveled by observer during the time lag between "registration" of the views seen by the uncovered and covered eyes (that is, latency difference multiplied by observer velocity); α_1, α_2, visual angles subtended by distance between near and far object as seen by uncovered and covered eyes, respectively; F, filter. (B) Far-object-fixed interpretation, with reconciliation of visual angles α_1 and α_2. (C) Near-object-fixed interpretation, with reconciliation of visual angles α_1 and α_2. Fig. 3 (right). (A) Near object fixed: factor by which estimate of the distance of far object (Fig. 2C) exceeds actual distance, as a function of the ratio D_2/D_1. Curves 1, 2, and 3 are for $\Delta = L/2$, $\Delta = L$, and $\Delta = 3L/2$, respectively. Curve 1 is asymptotic to $D_2/D_1 = 3$ (that is, apparent distance is infinity at $D_2 = 3D_1$), and, for values of D_2 greater than $3D_1$, the visual angles α_1 and α_2 cannot be reconciled without some displacement of the near object to a nearer position. Curve 2 is asymptotic to $D_2/D_1 = 2$; curve 3 is asymptotic to $D_2/D_1 = 5/3$. Plotted curves are solutions to the equation $K = D_1L/[D_1L - \Delta(D_2 - D_1)]$, assuming $D_1 \gg L$. (See Fig. 2A for definition of symbols.) (B) Far object fixed: factor by which estimate of the distance of near object (Fig. 2B) is less than actual distance, as a function of the ratio D_2/D_1. Curves 1, 2, and 3 are for $\Delta = L/2$, $\Delta = L$, and $\Delta = 3L/2$, respectively. Plotted curves are solutions to the equation $K = D_2L/[D_2L + \Delta(D_2 - D_1)]$.

these values are not unreasonable for normal reflected daytime illumination, some of the observational conditions under which the velocity illusion has been noted involved appreciably less illumination. If the extrapolation of laboratory measurements is valid, this implies a discrepancy for the increased velocity illusion (that is, when the covered eye is in a leading position). It may be, however, that the tiring of an observer experienced under apparently increased velocity and the occasional impression of confusion are reflections of some compensatory mechanism operative when apparent interocular distance would otherwise be negative; in this case, a 3-msec limit for the latency difference would not be a reliable determination.

Observations from a moving vehicle cannot, of course, readily provide quantitative data of the sort that can be easily obtained in a simplified laboratory situation with a swinging pendulum or oscillating target. Furthermore, the distortion of apparent distance, which is probably the "primary" illusion, seems to be entirely explicable as a constant-velocity corollary of the Pulfrich pendulum illusion. Nevertheless, there are several significant implications of the observed phenomena. The fact that the illusion from an automobile persists during prolonged exposure to uniform "target" velocity demonstrates both an independence of the effect from accelerations inherent in oscillatory motion and a general lack of accomodation. The "dwarfing" of objects of known size serves as a striking nonlaboratory demonstration of how compelling stereopsis can be as a determinant of distance perception, in the face of conflicting supplementary information. Furthermore, the distortions of subjective velocity, which seem entirely "reasonable" in a moving field in which distance is wrongly evaluated, provide evidence for the importance of stereoptic evaluations of distance as a factor in motion perception (*3*).

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References and Notes

1. C. Pulfrich, *Naturwissenschaften* **10**, 553, 569, 596, 714, 735, 751 (1922). Pulfrich himself (as have many others since) experimented not with a pendulum but with a peg oscillating on a linear pathway with sinusoidal changes in velocity.
2. R. H. Kahn, *Pfluegers Arch. Gesamte Physiol. Menschen Tiere* **228**, 213 (1931).
3. K. N. Ogle, in *The Eye*, H. Davson, Ed. (Academic Press, New York, 1962), vol. 4, p. 271.
4. M. H. Fischer and W. Mex, *Pfluegers Arch. Gesamte Physiol. Menschen Tiere* **252**, 478 (1950).
5. H. J. Engel and M. H. Fischer, *ibid.* **253**, 1 (1950).
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8. Full credit for noticing this illusion and bringing it to my attention goes to my son, Phillip N. Enright.
9. R. H. Kahn [*Pfluegers Arch. Gesamte Physiol. Menschen Tiere* **228**, 213 (1931)] reports, however, that, with considerable concentration and fixation on the oscillating pendulum bob, he was able subjectively to force the pendulum back into a planar oscillation, with the result that the rest of the room underwent startling oscillations in space.
10. Velocity, 80 km/hr = 22.2 mm/msec; a typical adult interocular distance is of the order of 60 to 65 mm.
11. This extrapolation is based on the data of Monjé [*Pfluegers Arch. Gesamte Physiol. Menschen Tiere* **249**, 280 (1947)] on the assumptions that latency difference at high intensities continues to be linearly related to the logarithm of the intensity and, on the basis of Lit's data [*Amer. J. Psychol.* **62**, 159 (1949)], that the slope of the relationship is proportional to the logarithm of the ratio of the intensity in the uncovered eye to that in the covered eye.
12. Supported by NSF grant GB 5471. I thank H. W. Honegger for helpful discussion of these results.

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Mercury: Surface Features Observed during Radar Studies

Abstract. *Radar studies of Mercury have shown the presence of several large, rough surface features and of one smooth area.*

Several large topographic features have been observed on Mercury during recent radar scans of that planet. The features appear to be almost continent-sized and are fixed to the surface and rotate with the planet. They have the ability to depolarize microwaves (12.5-cm wavelength) more strongly than neighboring areas do and are presumably rougher, to the scale of the wavelength.

The radar observations were made at the Jet Propulsion Laboratory's Goldstone tracking station in the Mojave Desert. Mercury is a very difficult target, having about the radar effectiveness of a dime at 16,000 km. The Goldstone radar facility, however, has tremendous capability which is summarized as follows: average power, 450 kw; wavelength, 12.5 cm; antenna gain (two-way), 4×10^{11}; and system noise temperature, 25°K.

Circularly polarized, monochromatic waves were beamed at Mercury. The weak returning echoes were no longer monochromatic. They were spectrally broadened by the Doppler effect which is caused by the rotation of Mercury. The actual data are in the form of spectrograms of the echoes, averaged over several hours to reduce the fluctuations of the noise.

Altogether, a dozen spectrograms were taken during the interval from 24 May to 13 June 1969. Half the data were taken with the receiver set for the expected sense of polarization of the echoes. These spectrograms show that much of the echoes originate from the quasi-specular region surrounding the sub-earth point.

The balance of the data was taken with the receiver set for the opposite sense of circular polarization, the so-called depolarized mode. The resulting spectrograms, weaker in power by a factor of 11, show topographic features

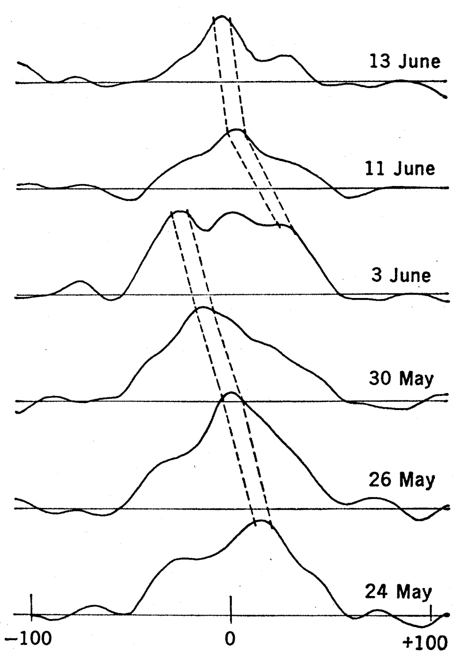

Fig. 1. Spectrograms of depolarized radar echoes from Mercury taken on six separate days. Power density is plotted against Doppler frequency shift. Spectral salients, corresponding to surface features on Mercury, are indicated by dashed lines.