images of the two frames renders information in the first frame more resistant to forgetting than information in the second: Most errors in the control condition were reports of a location that actually contained a dot in frame 1, not frame 2; in contrast, the reverse was true for two subjects in the saccade condition.

Thus, when two packets of information were presented at the same spatial location, but viewed during two different fixations so that their retinal locations were different, subjects saw the two packets as one image at the same spatial location. But when the spatial locations of the packets differed, even though the retinal coordinates were matched to the condition that produced integration, subjects saw two spatially separated images that they could not easily integrate. In both cases, perceptual experience reflects environmental events.

We hypothesize that the integration of information indicated by the saccade condition requires the use of a special memory, previously named an integrative visual buffer (*6*). Our experiment implies that packets of information with the same spatial coordinates, but different retinal coordinates, are properly aligned spatially in the buffer (*7*). This fused and spatially correct image is then available for further information processing (*8*).

At least two identifiably different memories may be involved early in the stream of visual information processing. One piece of evidence supporting this conclusion comes from a comparison of the time course of the integration phenomenon when the eyes move with the time course when no eye movements are required (*2*). Across subjects, accuracy increased as frame onset asynchrony increased from 164 to 184 to 224 msec (Table 1). This effect may obtain within a single subject as well: Subject 3 was rerun in the saccade condition with a signal to initiate his saccade before frame 1 onset, and with frame 1 durations of 27, 87, 127, and 167 msec (and hence, frame onset asynchronies of 64, 124, 164, and 204 msec). His accuracy was 41.9, 59.5, 53.5, and 63.4 percent, respectively. This result suggests that there is either an increase or no change in performance with frame onset asynchrony within the range investigated. In either case, it stands in contrast to that reported for integration within a single fixation (*2*), where accuracy decreases with increasing frame onset asynchrony within a similar range of values. This comparison suggests that different mechanisms underlie integration in the two contexts.

One intriguing possibility to account for these different effects is that early in the visual system, there is a storage site in which information is coded retinotopically, and in which this information is subject to integration and erasure effects by new entries that arrive within some time window. Later in the system, there may be another storage site that codes information by environmental coordinates, one that has a different set of time variables governing integration and erasure. Our results, along with the results of others, begin to lay the groundwork for investigating this second stage of information storage (*9*). This, in turn, offers a new opportunity to understand one of the most fundamental and intriguing of perceptual phenomena, the experience of a continuous visual world despite temporally discontinuous input.

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**References and Notes**

1. The problem is exacerbated by saccadic suppression, a phenomenon in which the quality of visual input during saccades is substantially reduced [E. Matin, *Psychol. Bull.* **81**, 899 (1974)].
2. V. DiLollo, *Nature (London)* **267**, 241 (1977); *J. Exp. Psychol.: Gen.* **109**, 75 (1980).
3. The eye monitoring equipment was sensitive to saccades of 0.5° and to deviations from fixation of even lesser extent.
4. Since the duration of frame 1 was set at the mean of subjects' saccade latency, and since there is variability around this mean in actual latencies, there were many trials in which subjects shifted their fixation either before frame 1 was extinguished or after frame 2 had been presented. These trials were excluded from analysis. The remaining trials that met the requirement stated in the text represent 44, 66, and 51 percent of the total for the three subjects, respectively.
5. Adequate precautions were taken to ensure that this persistence could not have been a function of the graphics display device itself.
6. K. Rayner, *Psychol. Bull.* **85**, 618 (1978).
7. Our experiments do not implicate any particular mechanism as the critical component in spatial reconciliation. It may be, for example, that extraretinal signals play an important role [H. von Helmholtz, *A Treatise on Physiological Optics*, J. P. C. Southall, Transl. (Dover, New York, 1963) (originally publ. 1909–1911); A. A. Skavenski, in *Eye Movements and Psychological Process*, R. A. Monty and J. W. Senders, Eds. (Erlbaum, Hillsdale, N.J., 1976)], or perhaps visual information from the retinal images themselves is sufficient [J. J. Gibson, *The Ecological Approach to Visual Perception* (Houghton Mifflin, Boston, 1979)].
8. Using time variables similar to ours, Matin has shown that people are poor at spatially reconciling the contents of two fixations to make relative position judgments [L. Matin, in *Handbook of Sensory Physiology*, vol. 7, part 4, *Visual Psychophysics*, D. Jameson and L. M. Hurvich, Eds. (Springer-Verlag, Berlin, West Germany, 1972)]. Using a different task, however, we have demonstrated that subjects can integrate information from two fixations to create a combined representation that has emergent perceptual properties (that is, a gap where no dot was presented).
9. M. Ritter, *Psychol. Res.* **39**, 67 (1967); C. W. Eriksen and J. F. Collins, *J. Exp. Psychol.* **77**, 376 (1968); M. L. Davidson, M. J. Fox, A. O. Dick, *Percept. Psychophys.* **14**, 110 (1973); W. Wolf, G. Hauske, U. Lupp, *Vision Res.* **18**, 1173 (1978); *ibid.* **20**, 117 (1980); J. Hochberg and V. Brooks, in *Eye Movements and the Higher Psychological Processes*, J. W. Senders, D. F. Fisher, R. A. Monty, Eds. (Erlbaum, Hillsdale, N.J., 1978).
10. Supported by NSF grant BNS 77-16887 and NIMH grant 1R03 MH36869-01. We thank J. C. Palmer for discussions about this research and for his invaluable contributions to the establishment of an eye movement laboratory.

7 August 1981; revised 9 November 1981

## How Do We Avoid Confounding the Direction We Are Looking and the Direction We Are Moving?

Abstract. *Contrary to a previous assumption, the center of the expanding pattern of visual flow is not generally useful as an aid in judging the direction of self motion since its direction depends on the direction of gaze. For some visual environments, however, the point of maximum rate of change of magnification in the retinal image coincides with the direction of self motion, independently of the direction of gaze. This visual indicator could be used to judge the direction of self motion.*

How does an airplane pilot or an automobile driver judge his direction of motion when vision is the only guide? One strategy would be to assume that the aircraft or car always travels at a fixed angle relative to the way it is pointing, but a pilot or driver using this strategy should expect directional judgments to fail when the aircraft yaws or when the car spins on ice. Other possible strategies have been suggested. Gibson (*1*) underlined the geometrical fact that, while an observer is moving forward, the retinal image of the outside world is necessarily undergoing continuous geometrical transformation. Figure 1, however, illustrates that, for a given direction of self motion, the retinal image flow pattern is strongly affected by the direction of gaze. Although previously noted (*2*), this point often seems to have been ignored in studies of visually guided locomotion (*3*). One consequence is that Gibson's much-quoted statement that the center or focus of the expanding flow pattern during forward motion corresponds to the observer's destination (*1*) is not generally correct. For the specific case illustrated in Fig. 1, Gibson's statement is not true if the observer looks at

  

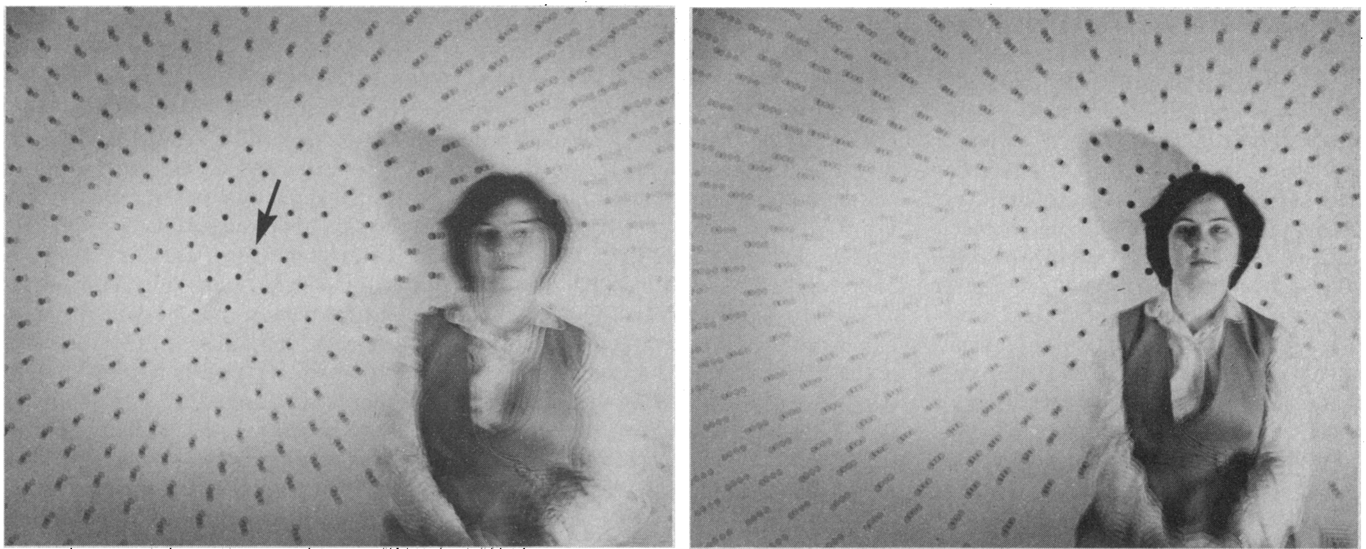

Fig. 1. Expanding flow patterns similar to those in the retinal image for an observer moving through the outside world. Multiple exposure (left) was taken with a camera moving toward the girl's head while pointing directly at the head. Multiple exposure (right) was taken with a camera moving toward the head while pointing to one side (arrow). The center of the expanding flow pattern did not coincide with the direction of motion, but with the direction of the camera's "gaze."

some point in the external world other than the point toward which he is moving. In this case, the flow pattern's center is displaced away from the direction of motion and coincides with the direction of gaze (*4*). We conclude that, contrary to Gibson's suggestion, the center of the expanding flow pattern in the retinal image does not provide a generally useful aid to accurately judging the direction of self motion (*5*).

We have searched for some feature of the transforming retinal image that could indicate the direction of self motion whatever the direction of gaze. One candidate is the local rate of change of magnification. For some visual environments, when an observer moves through the external world, the rate of change of magnification is greater at the retinal image of the point toward which he is moving than at neighboring points in the retinal image (*6*). Compared with the location of the center of the expanding flow pattern, the location of the maximum rate of change of magnification within the retinal image has the geometrical advantage of being independent of the direction of gaze. We investigated whether, in practice, subjects can accurately judge the position of a local maximum in the rate of change of magnification independently of direction of gaze.

As an external object we used a sine-wave grating for simplicity and because visual responses to such gratings have been much studied. This visual stimulus roughly corresponded to approaching an extended line of vertical fence posts, these posts appearing somewhat blurred. In our experiments the observer did not move. Instead we mimicked the spatial transformations of the retinal image caused by self motion by geometrically distorting the image of the sine-wave grating presented to the observer. The rationale of this experiment was to optically dissociate two aspects of the retinal image, namely the expanding flow pattern and nonuniformity in the rate of change of magnification.

The vertical 30 percent contrast grating stimuli were generated on the face of a cathode-ray tube (Tektronix, model 608) by a PDP 11/34 computer. Between stimulus presentations, the screen was uniformly illuminated and patternless. Each presentation consisted of a 2-second expanding pattern, starting from a uniform spatial frequency. (At the end of the presentation the spatial frequency was usually not uniform, being lowest at the point of maximum rate of magnification change). The motion of the pattern consisted of two components, one being an expansion and one an overall translational motion. Figure 2 illustrates three of the six expansions or spatial transformations. In terms of our notional line of fence posts, changing the value of $n$ can be regarded as planting the fence posts along a new curve. In separate experiments, we used different values of exponent $n$. While expanding, the pattern moved bodily sideways. Thus, at the center of the screen, the pattern never moved, though it moved everywhere else on the screen. Subjects fixated on the stationary center of the screen; a mark on the glass screen was provided to aid fixation. This mimicked the situation when a moving observer looks steadily at some fixed point in the outside world that is not necessarily his destination (*4*). The grating pattern contained a vertical black bar, created by blanking one whole grating cycle, which provided a reference mark on the pattern and mimicked a fixed reference mark in the outside world. In different presentations, the point of maximum rate of magnification was located either on the bar or at four different distances to the left or to the right of the black bar, and the black bar was located either at the center of the screen or at one of four different distances to the left or to the right of center. The nine different positions of the bar mimicked nine different directions of gaze relative to a fixed reference object in the outside world (that is, the black bar), and the nine different locations of the local maximum rate of magnification mimicked nine different directions of self motion for each direction of gaze. The rate of change of magnification was equivalent to the forward view from an automobile traveling at 55 km/hour directly at a wall 76 m away (*7*). With $n = 1.0$, the subject's task was to judge whether the center of the flow pattern was to the left or right of the black bar. With $n < 1.0$, the subject's task was to judge whether the maximum rate of change of magnification was to the left or to the right of the black bar. Feedback was provided. The 81 stimulus conditions were interleaved under computer control, and presentations continued until ten responses had been obtained for each condition. Thresholds were then computed by probit analysis.

Consider first the results for expansion patterns whose rate of change of magnification was uniform ($n = 1.0$) or nearly uniform ($n = 0.9$) over the whole visual field. With $n = 1.0$, subjects could not do the task at all. With $n = 0.9$, subjects either could not do the task or were only able to judge the direction of self motion to a very poor accuracy of about 5° to 10° (Fig. 3, A and B). All of these visual stimuli for $n = 1.0$ and $n = 0.9$ contained an expanding flow pattern with a clear center. These findings show that, contrary to Gibson's suggestion (*1*), the center of the expanding flow pattern in itself is not an effective visual stimulus for judging the direction of self motion.

Subjects performed differently for expansion patterns for which the rate of change of magnification was markedly greater along the (notional) direction of self motion than elsewhere ($n = 0.5$ and $n = 0.3$ in Fig. 3, A and B). For these stimuli, a subject's accuracy in the psychophysical task was as high as 0.03°. These stimuli contained a clear center of expansion, but in view of our results for $n = 1.0$ we assume that subjects were not using the location of the center of flow pattern expansion to judge the simulated direction of self motion. We suppose that subjects used the location of the maximum rate of change of magnification to judge the simulated direction of self motion. Figure 3, C and D, shows the progressive decay in directional judgment as exponent $n$ increased to unity. In our experiment, as in real-world scenes, the location on the retinal image of the maximum rate of change of magnification was not generally affected by the direction of gaze, even though the center of expansion may shift across the retinal image as the direction of gaze altered.

Our laboratory results suggest that, in real-world situations, subjects could not use the center of the expanding flow pattern to judge the direction of self motion. Our findings also suggest that, in judging the direction of self motion, differences in the rate of change of magnification across the retinal image may be of much more visual significance than the distribution of local retinal image velocity (*8*).

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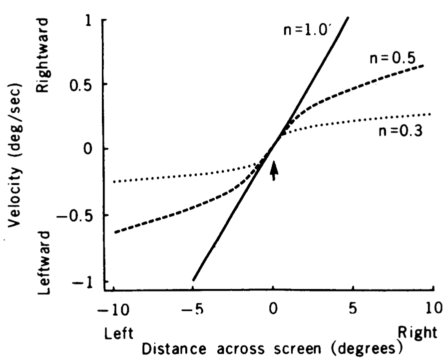
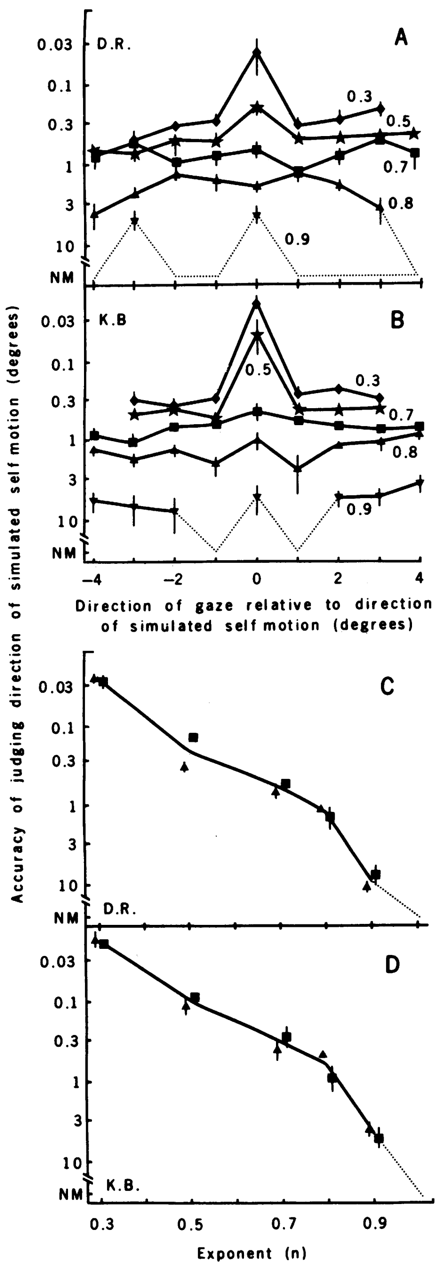



Fig. 2 (above). Three of the expanding flow patterns used in this study. The instantaneous velocity at any point in the pattern was first made a power function of distance across the pattern. Then a uniform translational speed was added to render stationary the pattern at the center of the screen (the point of gaze). Solid line, expansion pattern for which the rate of change of magnification was uniform across the pattern ($n = 1.0$). Dashed line, rate of change of magnification was slightly greater at one point in the pattern (arrow) than elsewhere ($n = 0.5$). Dotted line, rate of change of magnification was considerably greater at the arrow than elsewhere ($n = 0.3$). In different stimulus presentations the point of maximum rate of magnification occurred at the center of the screen or at various distances to left and right of center, but the pattern at the center of the screen was always stationary. Fig. 3 (right). (A and B) Subjects were not able to disentangle the direction of gaze from the direction of self motion when the rate of change of spatial frequency was uniform over the pattern ($n = 1.0$) and could hardly perform the task for $n = 0.9$, but when the rate of change of magnification was appreciably greater along the direction of simulated self motion, subjects were able to judge the direction of simulated self motion almost independently of the direction of gaze ($n = 0.8$, $n = 0.7$). For $n = 0.5$ and $n = 0.3$, subjects were somewhat more accurate when looking approximately along the direction of simulated self motion. The rate of expansion in all cases was equivalent to impact with the target 5 seconds after onset of stimulation. Initial spatial frequency, 5 cycle/deg. Field size, 16° vertical by 20° horizontal; mean luminance, 30 cd/m$^2$; and viewing was monocular. (C and D) Accuracy measured with subjects looking approximately along the direction of motion.




## References and Notes

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3. I. R. Johnson, G. R. White, R. W. Cumming, *Am. J. Psychol.* **86**, 311 (1973); R. Warren, *J. Exp. Psychol.* **2**, 448 (1976); D. N. Lee, *Perception* **5**, 437 (1976).
4. The eye (or head) rotates continuously when an observer looks at some object in the external world other than the object towards which he is moving.
5. W. Richards [in *Handbook of Perception* (Academic Press, New York, 1975), vol. 5, pp. 351–386] has shown that the retinal flow pattern is asymmetrical when the direction of gaze differs from the direction of motion. Symmetry might well provide a cue to the direction of self motion, but it seems unlikely that accuracy would be better than 10° to 20° even with a wide field of view.
6. When one is moving in a straight line at right angles to a plane surface, the maximum rate of change of magnification coincides with the point of impact on the plane. For inclined trajectories, the maximum falls at a point halfway between the point of impact and the closest point on the plane.
7. The fractional rate of change of magnification along the direction of motion is equal to the velocity of self motion divided by the distance to impact, that is, the reciprocal of time to impact. In our experiments, the rate of change of magnification was approximately constant during stimulation at 20 percent per second, so time to impact was 5 seconds.
8. That looming or changing-size detectors may be involved in detecting local magnification changes is suggested by findings with an expanding pattern whose magnification was constant except near the focus of expansion [D. Regan and K. I. Beverley, *Science* **205**, 311 (1979)].
9. We thank P. McInnis for writing the computer program used in this study. We thank M. Cynader, L. Kaufman, D. Quine, W. Richards, and K. Stevens for criticizing drafts of this manuscript. Sponsored by the Air Force Office of Scientific Research, Air Force Systems Command, under grant AFOSR-78-3711. K.I.B. was supported by the Natural Sciences and Engineering Research Council of Canada.

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