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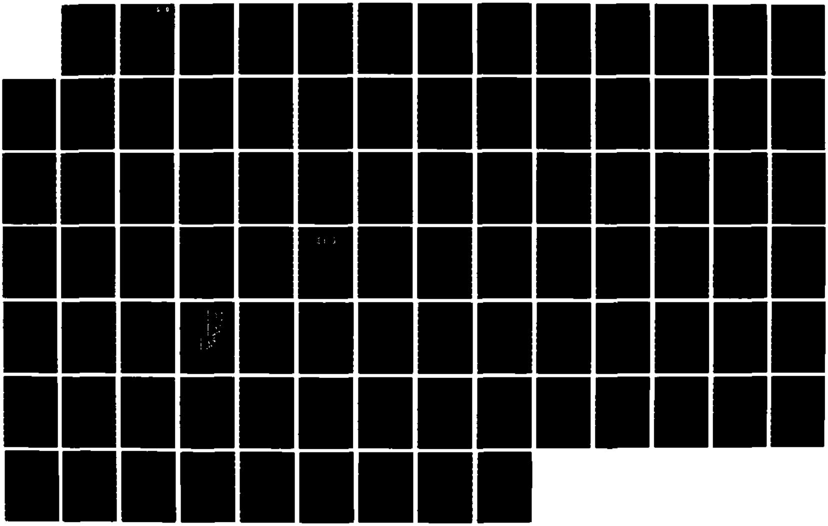

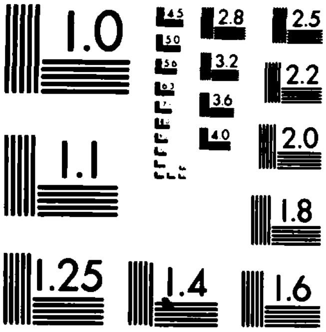

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Sensitivity to changing speed was studied with gratings of various spatial frequencies drifting across a screen while the average velocity was modulated. Thresholds expressed either as the velocity amplitude (difference between peak and average velocities) or as the maximum acceleration, increased monotonically with average velocity. The threshold for velocity contrast (velocity amplitude divided by average velocity) actually decreased with average velocity. The velocity contrast was minimal for velocity modulation frequencies of about 2 Hz and for spatial frequencies in the range of 2-4.5 c/d. In addition to these basic findings, we failed to find any effect of selective adaptation to changing speed other than that that could be attributed to smooth motion. It seems unlikely that mechanisms tuned to respond to changing speed per se are present in the human perceptual system. However, it is not possible to generalize from this to situations where higher derivatives are introduced by causing stimuli to change direction of motion.

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INTRODUCTION

This final report covers the period from January 1, 1982 to September 30, 1985. It details the work accomplished on our project entitled "The Perception of the Higher Derivatives of Visual Motion." This work is still going on, and another report will be issued on September 30, 1986.

As indicated by the title of the project, one of our major concerns was to study the sensitivity of the human observer to changing speed. In the past this sensitivity was often seen as related to the detection of the difference in speed of two moving targets. Also, there is some ambiguity as to whether detecting changes in speed is a strictly judgmental task rather than one involving sensory mechanisms specialized for the detection of changes in speed. Moreover, the effects of stimulus parameters such as spatial frequency content, average speed and temporal frequency have never been considered by those who studied sensitivity to differences in speed.

We shall not review the literature here, since it is reviewed elsewhere in this report. Thus, the literature related to the detection of differences in speed is reviewed in Sections 1 and 2 of this report. Section 1 is the draft of a paper supported by this project, and accepted for publication in Vision Research. The paper is being revised and will soon be published. Section 2 is a chapter written for the recently published "Handbook of Perception and Human Performance, Volume 1" (Boff, Kaufman and

Thomas; 1986). Work on this chapter was partly supported by the project being described in this report. The chapter traces the connections between the main subject of this project and other work in motion perception.

The goals of this project extend well beyond a concern for the sensitivity of the perceptual system to changing speed. More generally, we intended to deal with the perception of the higher derivatives of visual motion. These include acceleration and jerk. Acceleration is defined as the rate of change of velocity, and therefore may be introduced into a stimulus moving along a straght-line path by changing its speed. However, if speed is kept constant, acceleration may be introduced by changing the direction of motion. Therefore, to fully understand how the perceptual system deals with the higher derivatives of visual motion we must study the perception of changing direction of motion as well as that of changing speed. In addition, we must also deal with the rate of change in acceleration, the third derivative ("jerk"). Our efforts in this connection are still incomplete, but work is still going on. Section 3 of this report describes this ongoing work.

SECTION 1

Visual Sensitivity to Changing Speed

VISUAL SENSITIVITY TO CHANGING SPEED*

by L. Kaufman and S.J. Williamson
Departments of Psychology and Physics
New York University

It has been known for a long time that the sensitivity of the visual system to motion depends upon factors such as the duration of time that the target is visible, the luminance of the target and its contrast with its background, and the presence or absence of a visual framework. We know less about how such factors affect sensitivity to change of velocity (acceleration) or still higher deriviatives of visual motion. This paper describes an experiment designed to reveal some of the conditions that affect sensitivity to acceleration.

The amount of acceleration is the rate of change of velocity. Since velocity is a vector, having both direction and magnitude, acceleration can be introduced by changing either parameter. Thus, a target moving along a circular path may have a constant speed along the path, but it is none-theless accelerating, simply because it is always changing direction. In fact, a target moving at a uniform speed along a circular path of radius r can be regarded as having an acceleration v^2/r directed toward the center of the circle, where v is the instantaneous velocity of the target. A spot moving from side-to-side in a simple harmonic manner is also accelerating because it changes speed as well as direction as it moves. Alternatively, a spot moving in one direction accelerates if only its speed in that direction is changed.

Changing direction will not be considered in the present paper. Instead we shall deal exclusively with sensitivity to changing speed of a target moving in the frontal plane. There are two reasons for this restriction. First, changes in the direction of a moving target seem to be relatively easy to perceive. By contrast with the perceptual saliency of abrupt changes in direction, other evidence, to be reviewed below, suggests that changes in speed are not so easily detected. This implies that different mechanisms are involved in the two kinds of perception. This is consistent with the finding of directionally selective motion sensitive cells in the visual systems of several different species of animals (Barlow and Hill, 1963; Hubel and Wiesel, 1962, 1968; Zeki, 1974; van Essen, 1979). It is not known if such units respond to changing direction as well. Second, there is ample historical precedent for treating sensitivity to changing speed as a separate issue. In fact, the study of difference thresholds for velocity in one direction is a subject in its own right in the history of motion perception (Hick, 1950; Notterman, Cicala and Page, 1960; Mandriota, Mintz and Notterman, 1962). Thus, we leave the subject of acceleration due to changing direction for future work, and will restrict ourselves to considering factors that influence sensitivity to changing speed.

Models of directionally selective mechanisms for motion detection make no explicit provision for the detection of changing velocity (Barlow, Hill and Levick, 1964; Foster, 1971; Reichardt, 1961; Reichardt and Poggio, 1979). Although there is no logical impediment to revising such mechanisms, or to assembling them into higher-order detectors of non-uniform motion, the notion that changing speed can be sensed directly has been challenged in the literature. The question of whether or not there is a specific sensitivity to changing velocity in the frontal plane was raised by several workers, and this early work is ably reviewed by Gottsdanker (1956) who conducted some of the most interesting experiments dealing with this issue.

Gottsdanker (1952) had a target move along a horizontal path at a single uniform speed and also at two different non-uniform speeds, i.e., positively accelerating and negatively accelerating. All targets disappeared from view at some point after motion began, and the subject, who tracked the target with a stylus, was required to continue tracking after the disappearance of the target. By hypothesis, if the subject were able to sense the acceleration of the non-uniformly moving targets, then the tracking after disappearance should have continued to speed up at the appropriate rate. However, if the subject could not sense the acceleration, then tracking after disappearance should have been at a relatively uniform velocity, perhaps corresponding to the instantaneous velocity of the target at the time of its disappearance. While subjects did not actually track at the velocity of the target at the time it disappeared, they did continue to track at a uniform velocity. Such results led Gottsdanker to conclude that tracking was based on velocity or average velocity during some interval of time prior to the disappearance of the target. In fact, this study, and others as well, led him to suggest that subjects do not sense changing speed directly, but infer it by comparing velocity within one interval of time to velocity within another interval of time. Gottsdanker, Frick and Lockard (1961) obtained results consistent with this conclusion using another method. Subjects compared a target moving with a uniform velocity in one run with a target moving with either an accelerating or decelerating motion on another run, and had to decide on which of the two runs the motion was uniform. It was found that sensitivity to acceleration (as indicated by proportion of correct discriminations) decreased as mean velocity was increased. These authors also found that discrimination was adversely affected by decreasing presentation time. More importantly, they report that discrimination is more affected by the total change in velocity than by duration of the stimulus, a finding that is wholly consistent with the view that subjects simply compare early and late velocities. For later reference, it should be noted that minimum detectable changes in velocity were associated with initial and terminal velocities that differed by as little as 26% and as much as 157%, values that differ considerably from those reported by Notterman and his colleagues in their studies of difference thresholds for velocity.

More recently, Schmerler (1976) conducted a study that was similar to the study by Gottsdanker, Frick and Lockard (1961) in that subjects compared initial and terminal velocities of targets that moved at non-uniform velocities. Unfortunately, the results were inconclusive because the difference between the initial and terminal velocities at threshold was very variable, and did not vary significantly with experimental parameters. However, discrimination between initial and terminal velocity did improve when the target passed through an occluding tunnel in the course of a transit. This result is consistent with the notion that acceleration is detected by comparing different velocities.

Rosenbaum (1975) employed a somewhat different paradigm and came to a conclusion opposed to the conclusion of Gottsdanker and his colleagues and of Schmerler. In Rosenbaum's experiments the target was also occluded while moving. However, rather than have subjects compare velocities at different times, he asked them to determine when the hidden target whould intersect a visible marker on the path of the target. For a uniformly moving target, subjective velocity was highly correlated with objective velocity. In Rosenbaum's study the targets also accelerated as they moved across the screen. These too were occluded for a portion of their transit, and the subject had to decide when the occluded target intersected a visible marker.

Performance was best for the smallest of the three accelerations Rosenbaum employed. Here the objective acceleration accounted for 85% of the variance. However, for the highest acceleration only 5% of the variance could be accounted for. Thus, subjects appear not to be able to keep track of targets that are changing speed very rapidly.

A number of methodological problems beset these earlier studies. Among these is the fact that if a target is accelerating as it moves across the visual field, it is soon travelling so rapidly that it cannot be seen clearly. Also, the range and types of acceleration used in these studies was sharply constrained to a few conditions. Finally, the effects of abrupt onset and offset of the stimuli were not considered. Despite these problems, most earlier investigators concluded that acceleration is not directly sensed, but the judgment of a change in velocity is based on the detection of a difference in velocity, which is sampled at different times.

If the detection of acceleration is based on the detection of discrete differences in velocity, then the threshold for detecting a difference in velocity provides the main constraint in judging whether or not a moving target is accelerating. It is no simple matter to measure this threshold. For example, an abrupt change in velocity during the transit of a target introduces high second and third derivatives of motion, which may influence the results. Also, when a target is shown as moving at two different speeds at two different times, then the factor of memory must be taken into account. Finally, practice effects have been reported in the literature dealing with this subject.

The experiments described here were conducted to offset some of the problems alluded to above. Moreover, they were designed to include factors that were not explicitly incorporated in earlier work, such as spatial frequency and contrast characteristics of the target. We shall first describe the stimuli.

STIMULI

The stimuli were computer-generated gratings created by sinusoidally varying the luminance of a raster across the screen of a CRT. Three different spatial frequencies were used. These were 0.5, 2 and 4.5 c/deg. The average luminance of the screen was set at 40 cd/m^2, and the luminance contrast had one of 2 values, namely 0.2 and 0.5. These grating patterns drifted across the screen with one of three different average velocities, viz., 0.5, 2 and 5 deg/sec. The direction of motion was either to the left or right, with direction varied at random but frequently enough to prevent adaptation to one direction of motion. Luminance contrast was also randomized. Finally, the speed of the grating was sinusoidally modulated at one of four different modulation frequencies. These were 1, 2, 4 and 6 Hz.

METHOD

The purpose of the experiment was to determine the sensitivity to the non-uniform motion of a grating. The subject had to discriminate a grating whose speed was being modulated from one that was moving with a uniform speed, 75% of the time. To accomplish this, each of three subjects with normal vision were seated 140 cm from the display and were asked to fixate a small dark spot in its center. The display subtended about 8.4 deg horizontally and about 7.2 deg vertically. The latter is sufficient to insure maximum sensitivity to differential motion for the range of eccentricities encompassed by the horizontal span (McKee and Nakayama, 1984). Stimuli were presented for 2 sec each in pairs which were alike in all respects except that the speed of either the first or second stimulus was sinusoidally modulated. The subject had to choose which of the two moved with a nonuniform speed. High levels of modulation were used in the early trials, and this depth of modulation was reduced by half on succeeding trials. Thus, a modified staircase procedure was employed, with four staircases interleaved in any block of trials to determine the amount of modulation of speed needed to detect nonuniformity of motion 75% of the time.

These thresholds could be evaluated in many different ways. First the simple difference between the peak velocity of a grating and its average velocity could be used as the index of performance. This is called the "velocity amplitude". Second, by analogy with the Michelson contrast used in studying luminance contrast sensitivity functions, the difference between the peak and trough velocities (at threshold) divided by their sum is another measure of performance. The main advantage of this measure of "velocity contrast" is that it is equivalent to the classic Weber ratio, and thereby permits a direct test of the applicability of Weber's law to sensitivity to changing speed. A third measure is that of the "maximum acceleration" of the grating at threshold. This is proportional to the product of the velocity amplitude and modulation frequency.

RESULTS

An analysis of variance (ANOVA) was performed to determine if the threshold modulation amplitude was significantly affected by the luminance contrast, direction of motion and spatial frequency of the grating, as well as its average speed and the modulation frequency. In fact, no differences in threshold could be attributed either to the direction of motion or to the luminance contrast of the grating. Hence, these factors will no longer be considered. Intersubject differences accounted for only 5% of the variance at most and so was a relatively unimportant factor. However, modulation frequency had a significant effect on the modulation threshold, as indicated by Fig. 1a. The subjects appeared to be most sensitive to a modulation frequency of about 2 Hz, and were less sensitive to lower and higher frequencies of modulation. The effect of average velocity was also significant, accounting for 56% of the variance, and Fig. 1b show how the modulation amplitude threshold for detecting changing speed increases dramatically with average velocity. We shall consider this major effect below. Finally, while spatial frequency did not of itself have a significant effect on the threshold modulation amplitude, it did interact significantly with average velocity and modulation frequency.

The marked increase in threshold velocity amplitude with average velocity in Figure 1b suggests that "velocity contrast" might be a more meaningful measure of threshold, as opposed to the velocity amplitude. The resulting ANOVA was in some ways more revealing, for then the modulation frequency and average velocity achieved higher levels of significance and spatial frequency became a significant parameter. Figure 2a shows the variation of threshold with modulation frequency, and Figure 2b with average velocity. The interaction of average velocity and modulation frequency was highly significant and this interaction suggests that the coarse "tuning" of the visual system to a narrow range of modulation frequencies may become somewhat more coarse as average velocity is increased, as indicated by Figure 2b. It is particularly interesting that the contrast threshold, expressing the modulation amplitude as a percentage of the average velocity, was not constant, as would be implied by Weber's law. In fact, as shown in Figure 2b, the percent modulation in velocity needed to reach threshold actually decreased with average velocity. Owing to the transformation to velocity contrast for characterizing thresholds, the spatial frequency had a significant effect on velocity contrast at threshold, with the subjects generally being more sensitive to changing speed of the higher spatial frequencies than of the lowest with a suggestion of some tuning, as shown in Figure 2c. This figure also depicts a highly significant interaction between average velocity and spatial frequency. Finally, the interaction between modulation frequency and spatial frequency shown in Figure 3 displays a preferred tuning at about 2 Hz and 2 cycl/deg, with high spatial frequencies favored at low modulation frequencies.

The significant interaction between average velocity and spatial frequency suggests that the subjects may have been responding to the temporal frequency of changing luminance at a fixed point in the image of the display. For example, a rapidly drifting grating of low spatial frequency could produce the same periodic change in retinal illuminance at a point in the image as would a more slowly drifting grating of higher spatial frequency. This would be consistent with the conjecture by Smith and Sherlock (1957) that the velocity transposition effect described by J.F. Brown (1931) is due to the fact that subjects match temporal frequency and not perceived velocities. To check on this possibility we multiplied average velocity and spatial frequency to obtain temporal frequency, and found that stimuli of the same or nearly the same temporal frequencies but different average velocities and correspondingly different spatial frequencies also had profoundly different thresholds (expressed either as velocity contrast or as velocity amplitude (see Figure 4). Hence, we must rule out any systematic role for temporal frequency and conclude that in this experiment the predominant effect was that of velocity and modulation frequency per se.

The data were also transformed to discover if there was any systematic effect of average velocity and spatial frequency on the maximum acceleration of the grating per se. As already indicated, the maximum acceleration is proportional to the product of the modulation frequency and the modulation amplitude. In fact, as shown in Figure 5, there is a remarkable uniformity in this transformation of the data, since acceleration at threshold increases by almost a factor of 10 as average velocity increases by this factor. This suggests that the visual system is not responding to acceleration per se. A relatively small amount of acceleration may be detected when the average velocity in which it is superimposed is low, and the acceleration must be much larger when the average velocity is relatively high.

The results of this experiment suggest that sensitivity to changing speed is high over a relatively narrow range of conditions. These conditions are satisfied when the average retinal speed of the target must be within the range of velocities used in this experiment. In fact, pilot studies indicated that with velocities much higher than 5 deg/sec, stationary fixation, and with the spatial frequencies we used, it is simply not possible to perform the task. Also, detection is generally better for higher spatial frequencies and intermediate modulation frequencies. We offer the following speculative interpretation of these major results: Sensitivity to changing speed can be of great value to the occulomotor system in visually tracking a moving target. If tracking is successful, then the average velocity of the target on the retina will be relatively slow, and if the eye is to correct errors as they develop, the visual system must be capable of detecting slow changes in that velocity. This is less critical for targets composed of lower spatial frequencies, since there is no fine detail to be maintained in the fovea and therefore lower sensitivity to velocity change can be tolerated. Also, for very rapidly moving targets the most vital information for the visual system is the first-order term, namely the velocity of the target. This information is used to "catch-up" to the target, and then a finer control system may take over, and this system could employ higher derivatives of motion to sustain accurate tracking. Hence, it is not surprising that much higher levels of acceleration are needed to detect non-uniformity of motion when the grating of our experiment are moving rapidly. All of this suggests that there is indeed a capacity for sensing changes in velocity, albeit over a very limited range of conditions.

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** We wish to thank Aries Arditi, David Dorfman and Reid Tanenbaum for their help and advice.

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LEGENDS

Figure 1

(a) Threshold velocity amplitude as a function of modulation frequency. Dashed lines show variation for different average velocities, and the solid line is the average across all average velocities

(b) Threshold velocity amplitude as a function of average velocity. Dashed lines show variation for representative modulation frequencies with the solid line giving the average across all modulation frequencies.

Figure 2

(a) Threshold velocity contrast as a function of modulation frequency. Solid line is averaged over thresholds obtained at various average velocity (dashed lines).

(b) Threshold velocity contrast as a function of average velocity. Soild line is average of thresholds obtained for different modulation frequencies (dashed lines).

(c) Threshold velocity contrast as a function of average velocity. Solid line is average of thresholds obtained for different spatial frequencies (dashed lines).

Figure 3

Threshold velocity contrast as a function of spatial frequency for various modulation frequencies (dashed lines) and the average over all modulation frequencies (solid line).

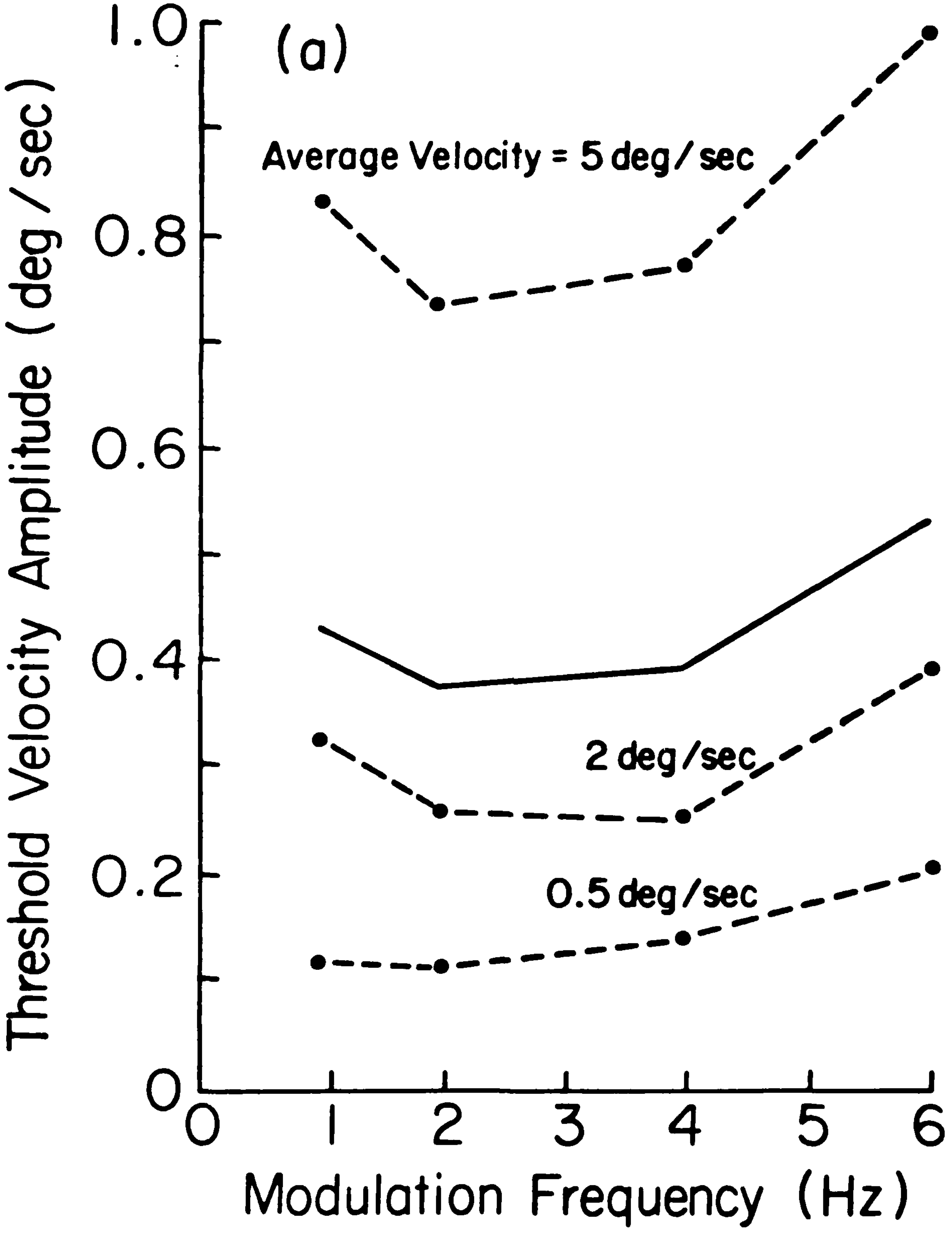
Figure 4

Threshold velocity contrast is not a single-valued function of temporal frequency at 1 Hz, and between 2.25 and 2.5 Hz it displays a marked change.

LEGENDS (Continued)

Figure 5

Threshold maximum acceleration as a function of average velocity. Solid line is average of thresholds over different spatial frequencies (dashed lines).


(a)
Average Velocity = 5 deg/sec
2 deg/sec
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Threshold Velocity Amplitude (deg / sec)
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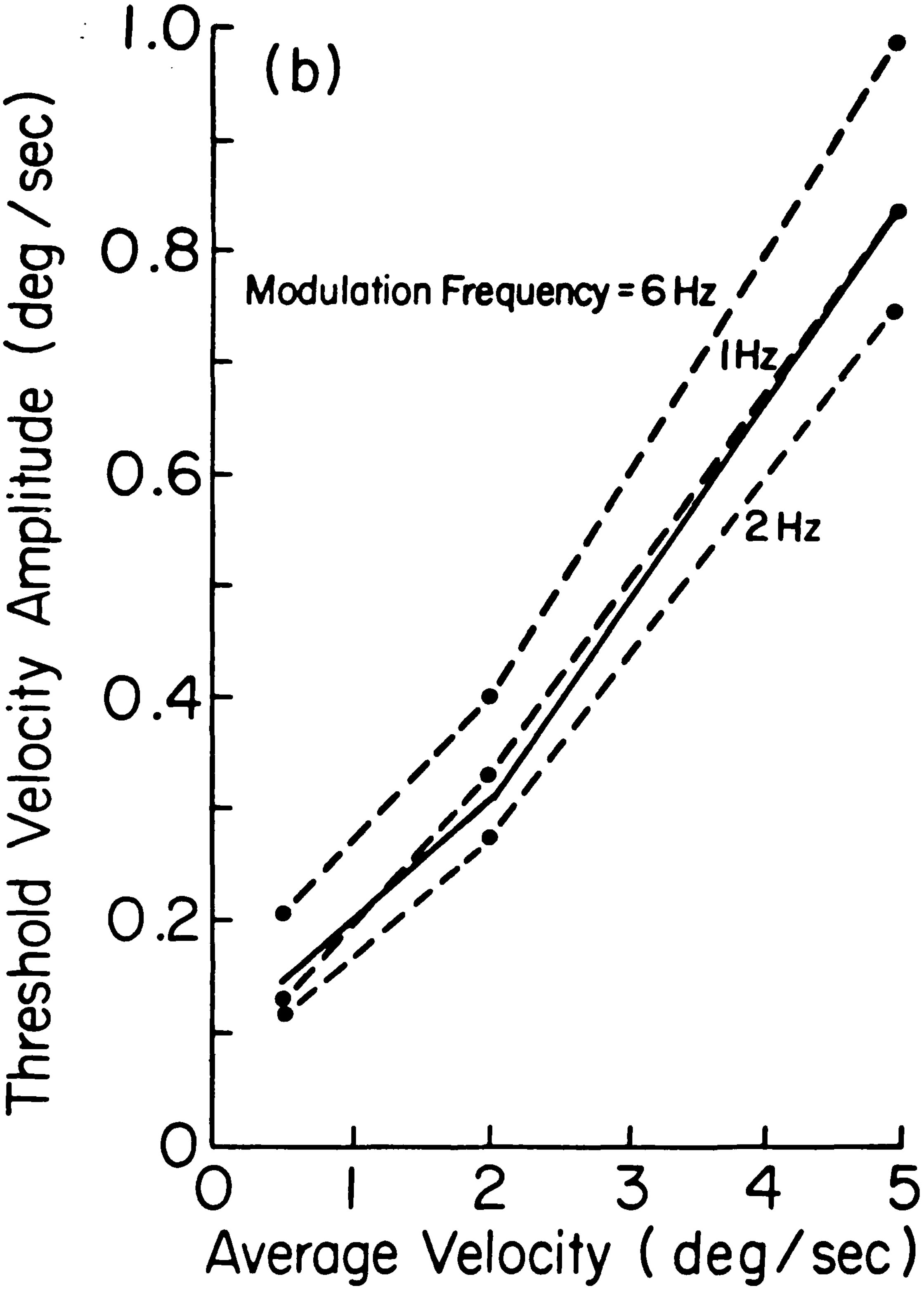
0.6
0.4
0.2
0
0
1
2
3
4
5
6
Modulation Frequency (Hz)


(b)
Modulation Frequency = 6 Hz
1 Hz
2 Hz
Threshold Velocity Amplitude (deg/sec)
Average Velocity (deg/sec)
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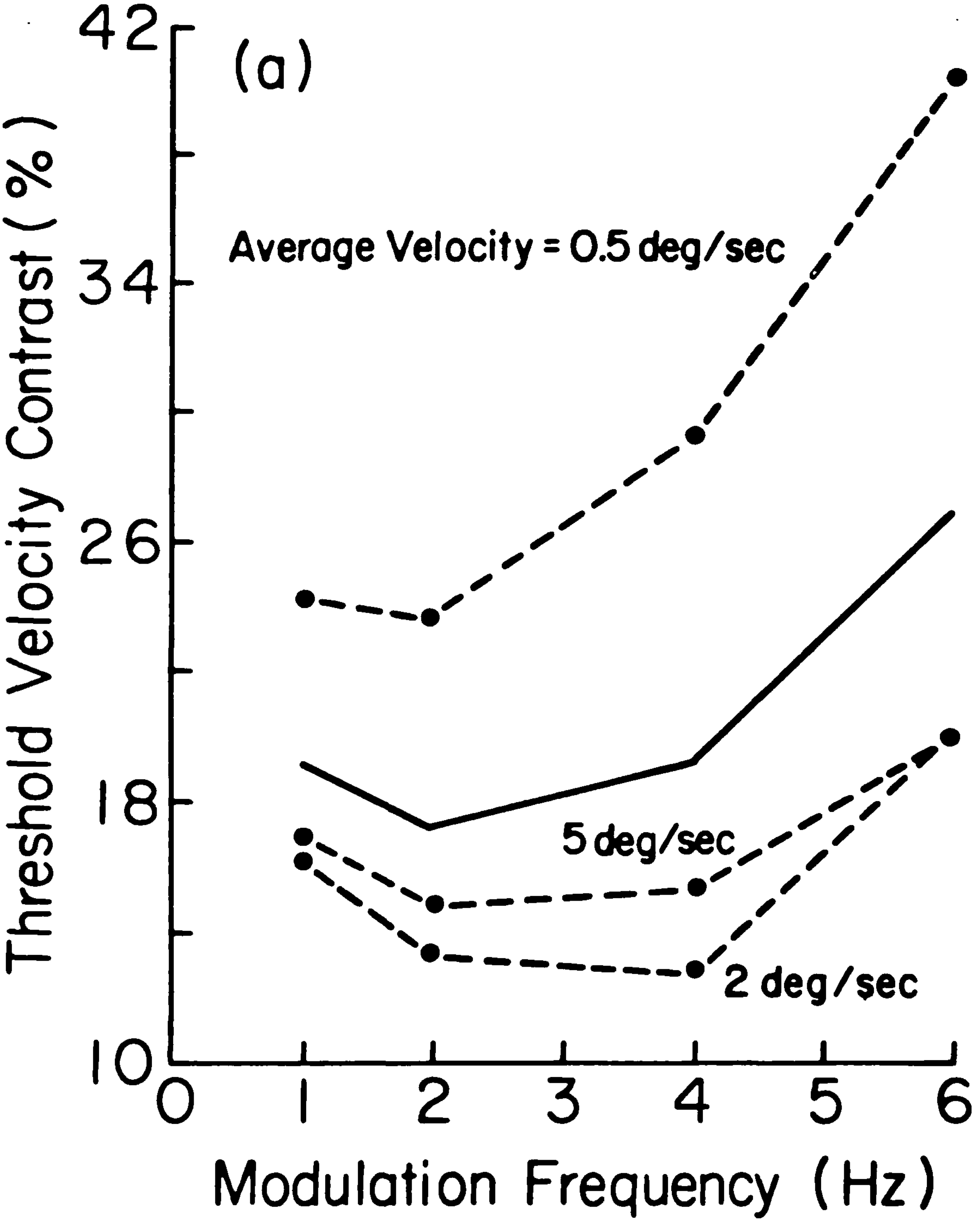
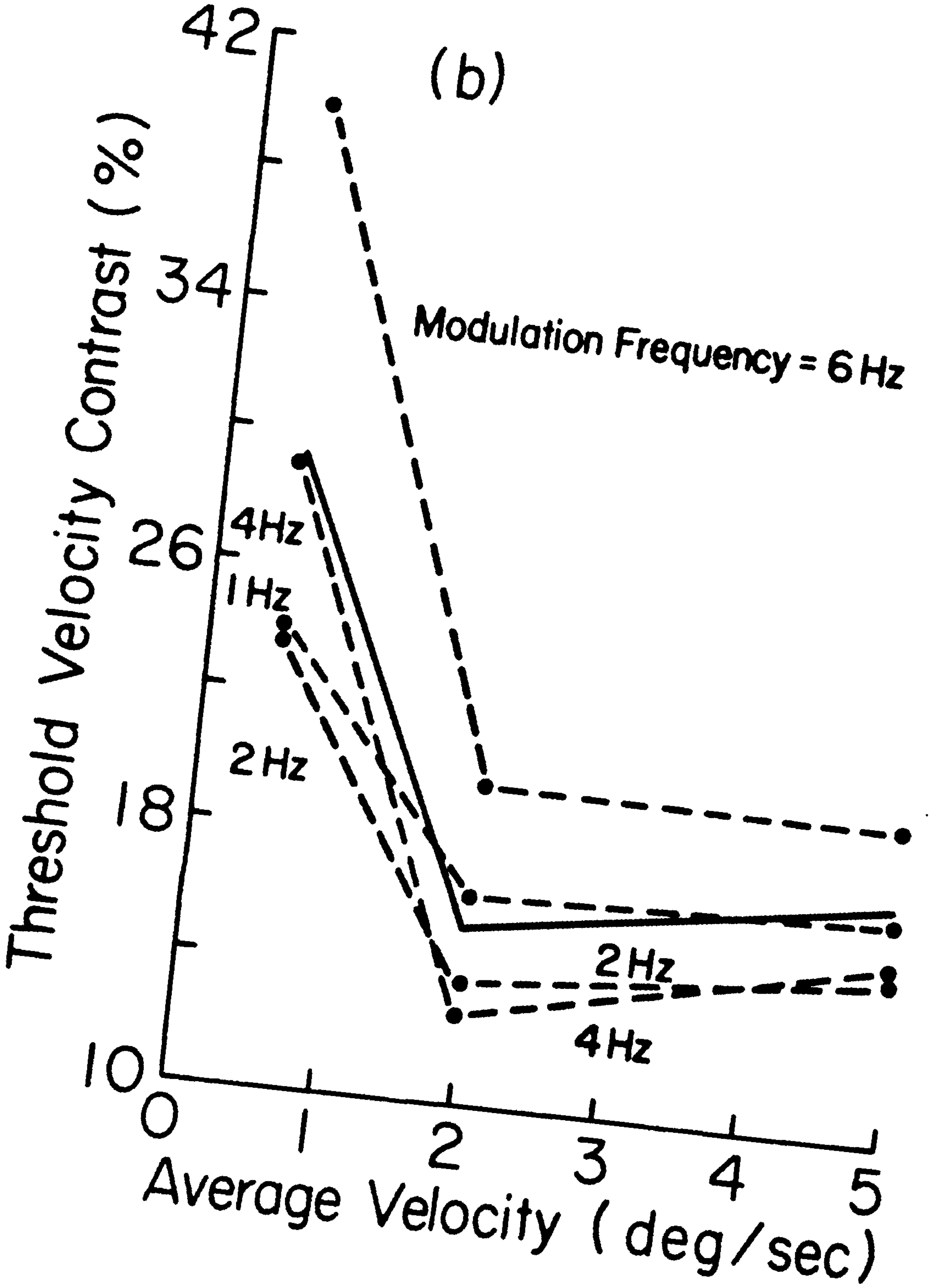
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
5


(a)
Average Velocity = 0.5 deg/sec
5 deg/sec
2 deg/sec
Threshold Velocity Contrast (%)
42
34
26
18
10
0
1
2
3
4
5
6
Modulation Frequency (Hz)


(b)
Modulation Frequency = 6 Hz
4 Hz
1 Hz
2 Hz
2 Hz
4 Hz
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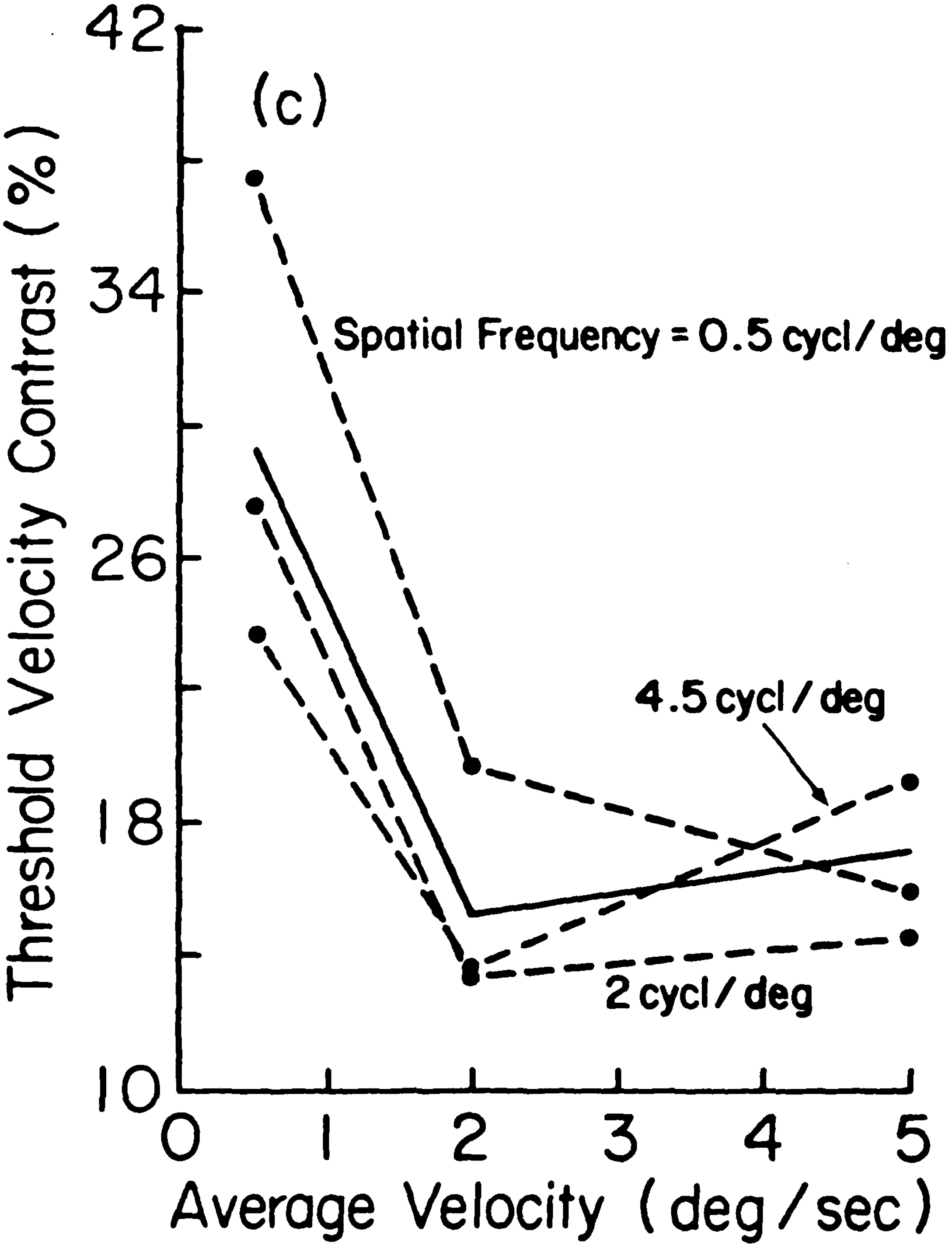
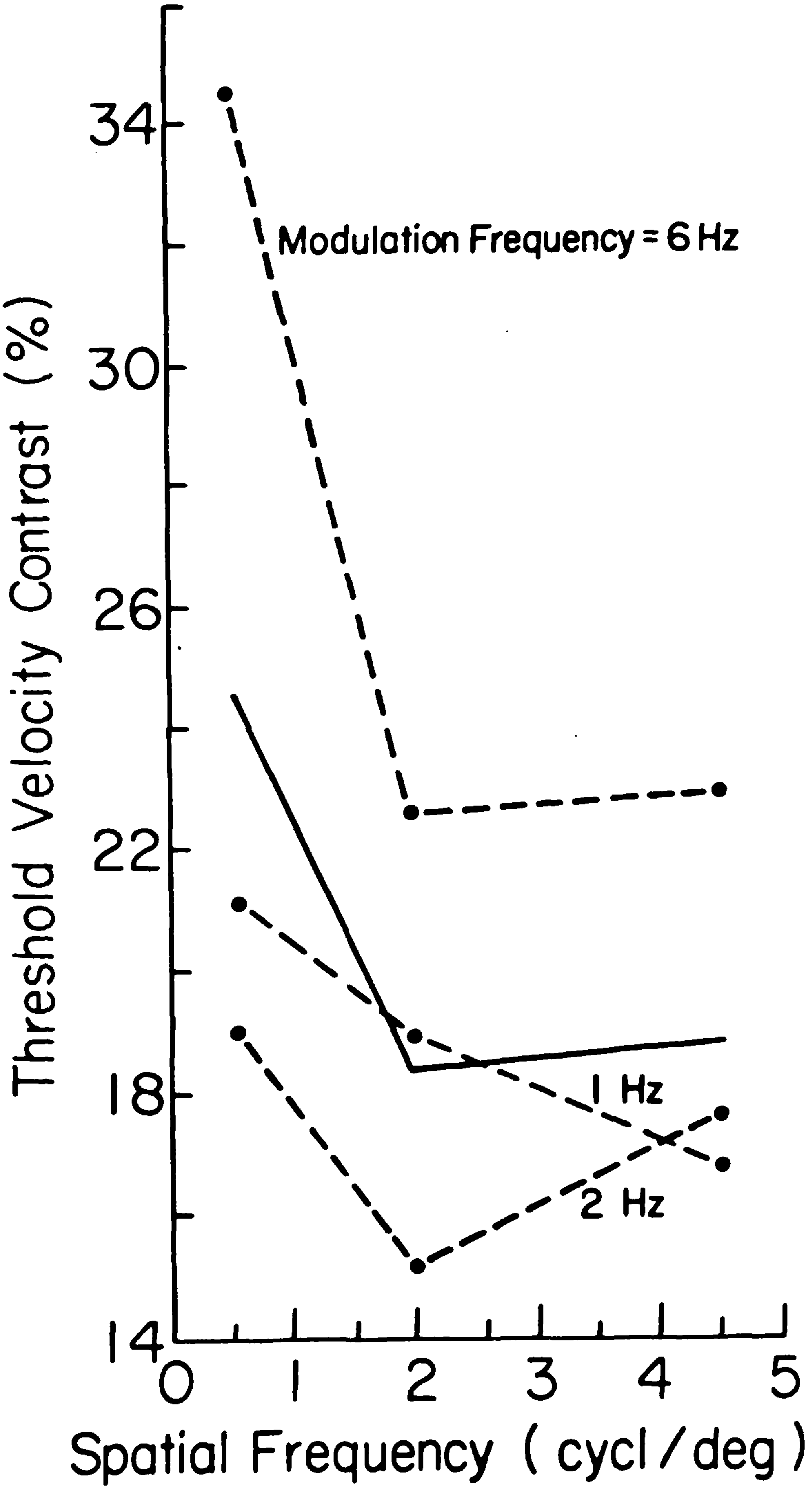
42
34
26
18
10
0
1
2
3
4
5
Average Velocity (deg/sec)


(c)
Threshold Velocity Contrast (%)
42
34
26
18
10
Spatial Frequency = 0.5 cycl/deg
4.5 cycl/deg
2 cycl/deg
0
1
2
3
4
5
Average Velocity (deg/sec)


Modulation Frequency = 6 Hz
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2 Hz
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22
18
14
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1
2
3
4
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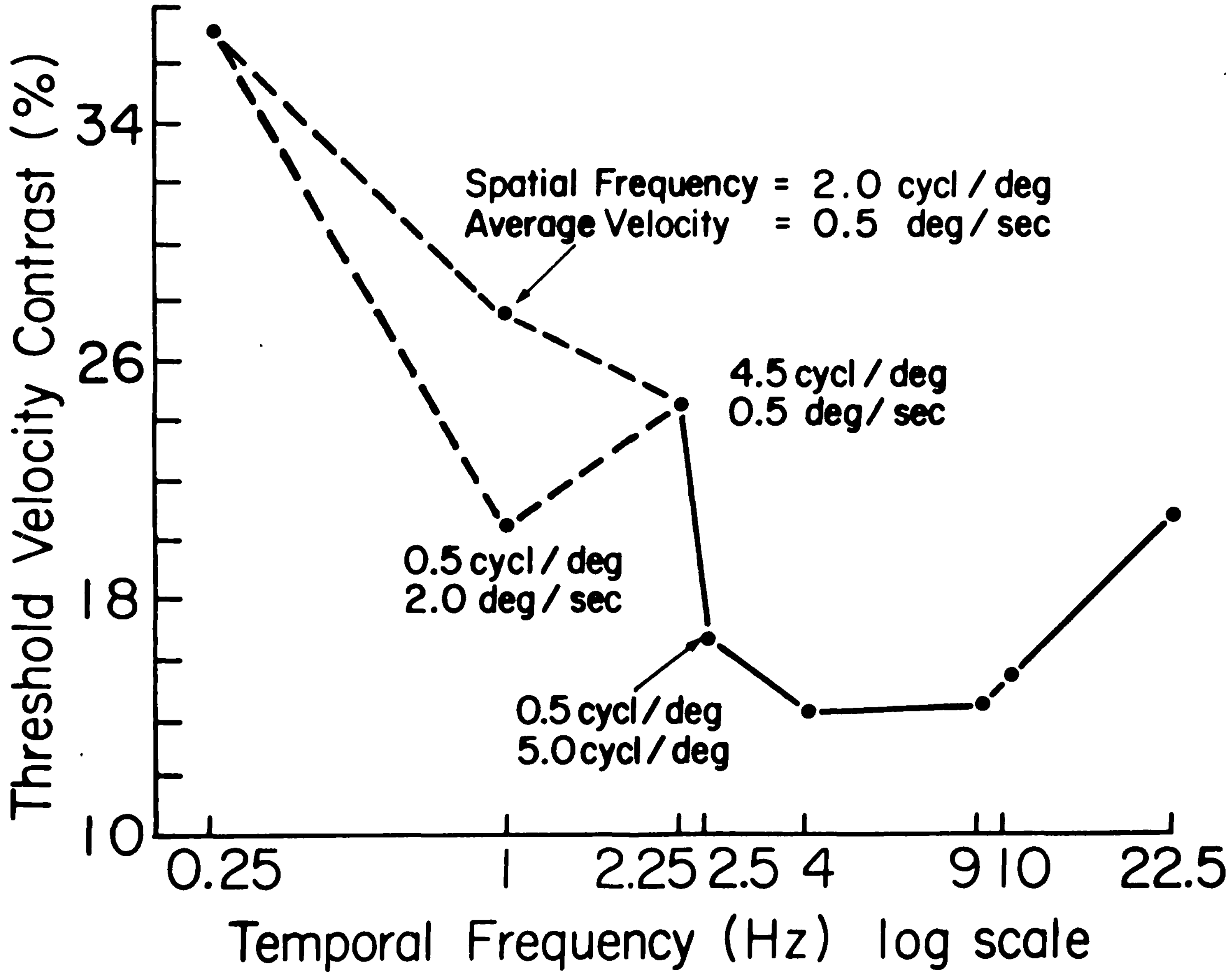
Threshold Velocity Contrast (%)
Spatial Frequency (cycl / deg)


Threshold Velocity Contrast (%)
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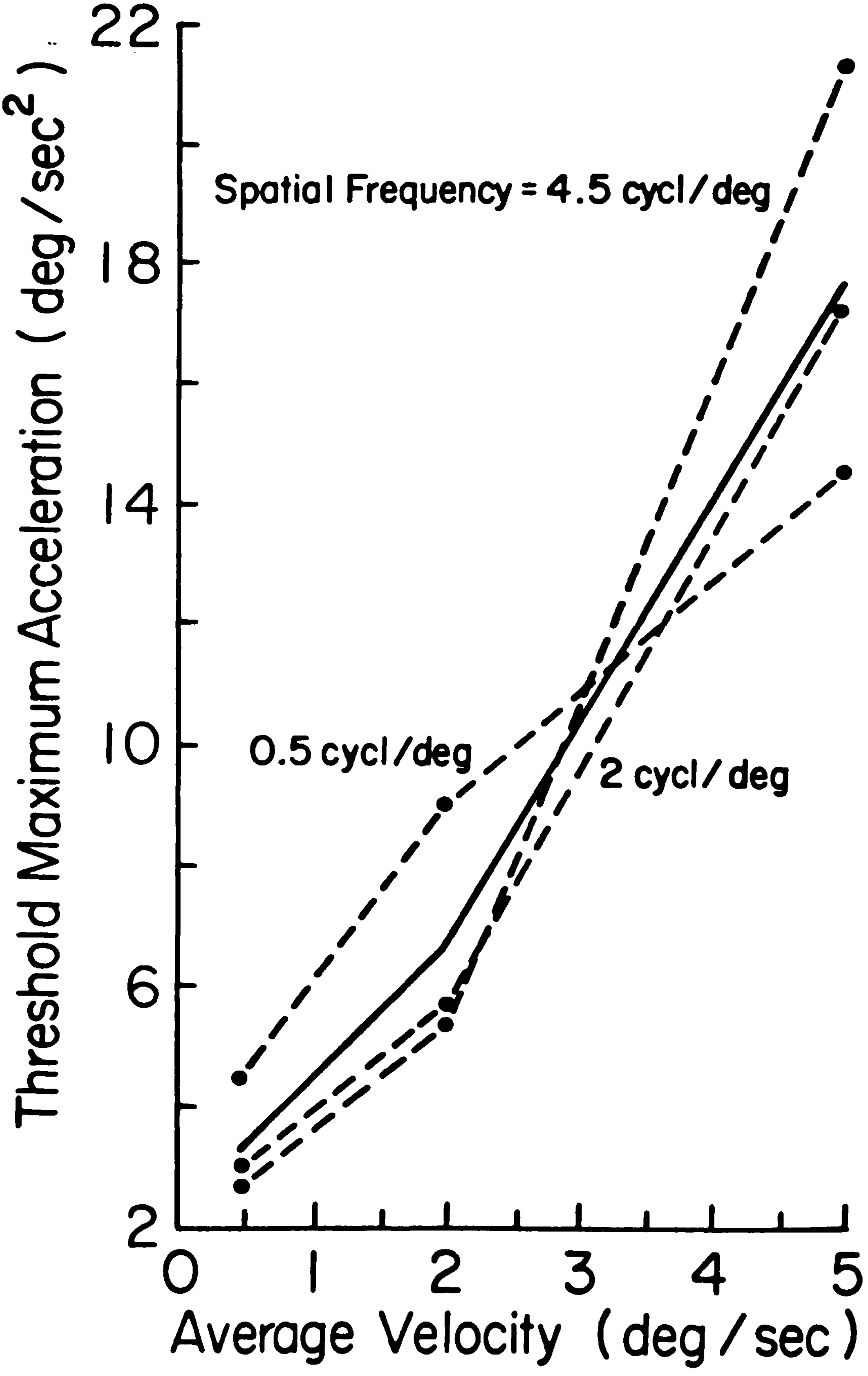
26
18
10
0.25
1
2.25
2.5
4
9
10
22.5
Temporal Frequency (Hz) log scale
Spatial Frequency = 2.0 cycl / deg
Average Velocity = 0.5 deg / sec
4.5 cycl / deg
0.5 deg/ sec
0.5 cycl / deg
2.0 deg / sec
0.5 cycl / deg
5.0 cycl / deg


Threshold Maximum Acceleration (deg / sec^2)
22
18
14
10
6
2
Spatial Frequency = 4.5 cycl / deg
0.5 cycl / deg
2 cycl / deg
0
1
2
3
4
5
Average Velocity (deg / sec)

SECTION 2

Motion in Depth and Visual Acceleration

MOTION IN DEPTH AND VISUAL ACCELERATION

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CHAPTER 19

MOTION IN DEPTH AND VISUAL ACCELERATION

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CONTENTS

Motion perception is one of the central topics of this *Handbook*. Apparent motion, aftereffects of exposure to motion, induced motion, and the visually induced sense of self-motion (vection) are discussed by Howard, Chapter 11, Mack, Chapter 17, and Rock, Chapter 33. Thresholds for seeing motion are considered in Chapter 16 by Anstis. This chapter goes further in discussing motion that is nonuniform in time or in space. For example, the velocity of a ball thrown through the air is not uniform in time, but changes from instant to instant. The velocity at any point on a river's surface may remain constant from moment to moment, but the velocity is different at different locations on the water's surface. Section 1 discusses motion that is nonuniform in time and is especially concerned with sensitivity to the acceleration of targets moving in the frontal plane; Sections 2 and 3 discuss motion that is nonuniform in space. Section 2 discusses empirical results of studies of perceived motion in depth due to changing size and to changing disparity, which produces effects that differ from the classic static disparity discussed by Arditi in Chapter 23. Section 3 deals with the direction of self-motion in depth and with optic flow patterns, for the two subjects are strongly related to each other.

A pervasive concept in vision research is that the visual system has multiple specific sensitivities; the visual system responds to some specific abstract feature of the retinal image, rather independently of other stimulus parameters, and there are a limited number of these specific sensitivities. (See Chapter 6 by Watson, Chapter 34 by Ginsburg, and Chapter 35 by Treisman in this *Handbook* for discussions of related concepts.) It has been suggested that the effect of these multiple sensitivities is to make an initial analysis of the retinal image by reducing the available information to a limited number of dimensions, without recourse at this stage of perception to any conscious or unconscious inferential processes. A component mechanism underlying such specific sensitivity is exemplified by a hypothetical "motion detector" in the visual system that is selectively sensitive to movement of the image across the retina. As we shall see in Section 1.1, such a component is insufficient to account for detection of nonuniformity in the motion of the image over time and other processes must be postulated at a later stage which, in this case, could include an inferential process.

Without denying the likelihood that higher-order processes may follow the analysis of the proximal stimulus by the visual system, a central theme in this chapter is to use the "multiple specific sensitivity" idea to explain visual responses to motion that is nonuniform in space. Section 3 discusses experimental evidence that the human visual system is specifically sensitive to certain relationships between the velocities at different locations in the retinal image, and that there are several such specific sensitivities to spatial relationships. One example of specific sensitivity is the visual response to looming or changing size; the visual system responds accurately to the algebraic difference between the simultaneous velocity at two locations that can be a degree or so apart in the visual field. Because this is a sensitivity to a relationship between two velocities, it cannot be explained in terms of classic sensitivity to velocity, for example, in terms of the action of simple "motion detectors." However, unlike sensitivity to nonuniform motion in time (which also cannot be explained solely in terms of simple motion detectors), evidence exists to support the applicability of the concept of "specific sensitivities" as an explanatory device.

Section 3.1 discusses visual responses to optic flow patterns produced by self-motion in terms of specific sensitivities to relationships between velocities at different locations. The approach is to identify by experiment those specific sensitivities that exist in the visual system, as well as those that are absent. Flow pattern parameters to which the visual system specifically responds seem more likely to be behaviorally significant than cues to which the visual system does not respond in any specific manner.

The spatial distribution of velocities in an optic flow pattern can be described in the notation of vector analysis (vector calculus). In this formalism, the spatial properties of the flow pattern are described in terms of the mathematically independent quantities grad V, div V, and curl V, where V is the local velocity at any given instant. The Appendix provides definitions of the terms "div," "grad," and "curl," but for those unfamiliar with vector calculus the book by Schey (1973) contains an excellent introduction. Section 3 summarizes experimental evidence that the human visual pathway is selectively sensitive to attributes of the optic flow pattern caused by self-motion that roughly approximate div V and also may be sensitive to a rough approximation of curl V.

Section 4 discusses specific multiple sensitivities in the context of channel theories of motion in depth. This example illustrates how such theoretical notions may lead to useful practical results. This point is elaborated in Section 5, which discusses applied research in which the "multiple specific sensitivity" idea informed the study of flying performance in simulator and real aircraft.

1. VISUAL ACCELERATION

1.1. Background

As the eye moves to scan a scene, the images of stationary objects in that scene move across the retina. However, in normal circumstances the objects are not perceived as moving. Also, a stationary target within a moving frame may be perceived as moving opposite to the direction of motion of the frame (induced motion). The general conclusion from such observations is that a single mechanism cannot be the basis for sensing motion.

Chapter 17 by Mack, Chapter 22 by Hochberg, and Chapter 21 by Sedgwick distinguish between *object-relative motion* and *subject-relative motion*. Although this distinction (and the similar distinction between *exocentric* and *egocentric* motion) is of considerable theoretical interest, we do not dwell on it here. Instead we deal with processes that are presumed to underlie both kinds of motion, namely those related to information associated with image translation across the retina and eye-head motion involved in tracking objects.

Although several mechanisms must be postulated in models designed to explain the perception of motion, we do have knowledge of one type of mechanism that can account for the detection of motion in the frontal plane. Cells in the visual system of the cat (Hubel & Wiesel, 1962), rabbit (Barlow & Hill, 1963), and monkey (Hubel & Wiesel, 1968) respond when bars or edges are moved across their receptive fields. In fact, the majority of motion-sensitive neurons in the medial temporal cortex of macaque respond to movement in one direction only (van Essen, 1979; Zeki, 1974). Also, some neurons in primary visual cortex respond to unidirectional motion in depth (Cynader & Regan, 1978; Poggio & Talbot, 1981).

The existence of such cells in the cortex suggests that velocity is directly encoded at a relatively early stage of visual processing in parallel with the detection of successive positions of a target over time. One model of a system capable of detecting motion relative to the retina in a single direction is schematized in Figure 19.1.

There are several possible variations of the scheme depicted in Figure 19.1. For example, if unit t should respond in a sustained manner some time after stimulation of R_1, then the movement detector would respond regardless of the speed of the stimulus as long as it exceeded some minimum value. In this case the circuit would detect movement over a wide range of speeds, provided they were not too great, and the narrowness of its velocity tuning would thus be reduced. An alternative scheme is to have the detector perform an analog operation, such as multiplication. Such directionally selective movement detectors have been proposed by Barlow, Hill, and Levick (1964), Foster (1971), Poggio, Reichardt, and Hausen (1983), Reichardt (1961), and Reichardt and Poggio (1979).

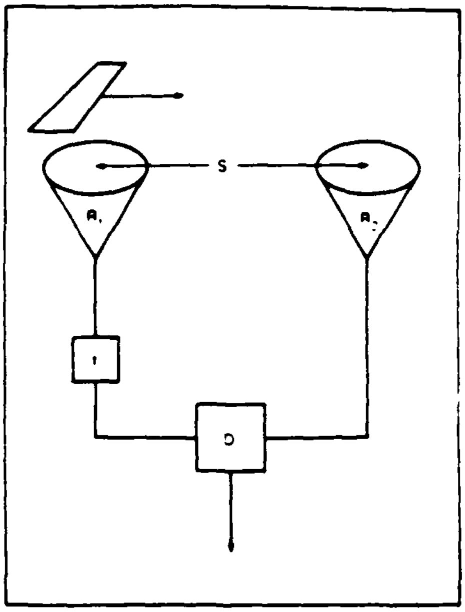


Figure 19.1. Schematic version of a model of a polarized velocity detector. When the image of the bar stimulates receptor R_1, the unit t delays the output of R_1 before transmitting it to the movement detector D. If the bar arrives at R_2 concurrently with the arrival of the output of t at D, the movement detector responds to the coincidence of the signals originating at R_1 and R_2. This movement detector cannot respond when the bar moves from R_2 toward R_1. (From L. Kaufman. *Sight and Mind*, Oxford University Press, 1974. Reprinted with permission.)

Anstis and Rogers (1975) suggested that motion detectors could be incorporated in a network analogous to the projection field employed in some models of stereopsis (see Chapter 23 by *Arditi*). *In this application each point in one eye may interact* with many other points in the same eye. The resulting network effectively multiplies events occurring at one point with events occurring at other points. This multiplication is similar to the cross-correlation presumed to be involved in the detection of disparity in a projection field (Kaufman, 1974).

As pointed out by Arditi, to obtain stereopsis the perceptual system must match corresponding stimuli of the two eyes to avoid the problem of "ghosts," that is, the fusion of unrelated points imaged in the two eyes. The same is true in motion perception, where the problem is referred to as that of phenomenal identity (Ternus, 1938) or, alternatively, as the problem of correspondence (Ullman, 1979). In motion perception, an image formed at different places and times on the retina must be identified as belonging to the same object. A cross-correlating network could make it possible to solve the problem of identity by comparing the retinal image at one time with the image at other times. In fact, virtually all theories of the perception of motion based on translation of the images of objects across the retina incorporate the operation of cross-correlation.

All versions of the basic cross-correlation model described above fail to distinguish between targets that move with the same average speed but whose speed changes as they traverse a portion of the retina. Consider the simple model shown in Figure 19.1. If a target moves rapidly across R_1 and then slows down before reaching R_2, the motion detector would still respond. Now, if the perceptual system is capable of sensing acceleration directly, as it presumably senses velocity, either a second-order correlation process must occur—for example, the comparison of three representations of the retinal image occurring at three different times—or a comparison of velocities must occur at some higher level. In this chapter we consider the evidence concerning the sensitivity of the perceptual system to change of speed per se.

Thus far we have restricted discussion to the so-called *image-retina* system (Gregory, 1966). This is the hypothetical system that uses information about the translation of an image across the retina to compute the motion of the image. Motion may also be perceived when the eye and head are rotated to track a moving target. Theoretically, this need not involve the image-retina system for, in such cases, the retinal velocity of the image may be zero. The eye-head system (Gregory, 1966) is presumed to be capable of detecting motion even when there is little or no slip of the image on the retina. This actually occurs when an afterimage is seen to move during voluntary eye movements, and it makes it possible for the observer to fixate a moving target (to prevent its becoming blurred due to high retinal velocity) and still detect the motion. To a first approximation, the velocity given by the image-retina system is added to the velocity given by the eye-head system to obtain the net velocity of the target. Of course, the two systems are not equally sensitive; that is, a target moving across the visual field while the eye is stationary appears to move more rapidly than it does when it is tracked by the eye (see Mack, Chapter 17), and therefore are not given equal weight in the perception of speed. Even so, as Gregory (1966) proposed, there can be little doubt that they work in tandem.

It appears that the eye-head system is capable of responding to the nonuniformity of motion. Although there is little evidence that proprioceptive feedback enables observers to consciously monitor eye position during smooth pursuit eye movements (Festinger, Sedgwick, & Holtzman, 1976), observers can still move their eyes with great precision in tracking a target moving with a nonuniform velocity. Moreover, Purkinje cells in the cerebellar flocculus fire in step with the eyes as they move in smooth pursuit of a sinusoidally moving target (Noda, 1981). There is substantial evidence that the control of eye movements in visual tracking tasks is mediated by the cerebellum (Lisberger & Fuchs, 1978; Miles & Fuller, 1974; Miles, Fuller, Braitman, & Dow, 1980; Noda & Suzuki, 1979). It seems likely that the cerebellum is effectively "programmed" to accomplish fine motor control, as in oculomotor tracking, and that it is capable of extracting higher derivatives of motion to make such tracking possible (Pellionisz & Llinas, 1979). Even if true, it does not necessarily follow that the nonuniformity of motion is consciously perceived.

As we shall see below, much of the evidence to date suggests that acceleration is not directly sensed by the perceiver, although the question is still open. In fact, most theorists assume that the observer infers the presence of a change in speed from the fact that velocity at one time differs from velocity sensed at some other time. Hence the critical data in this area are those pertaining to difference thresholds for velocity. These thresholds were measured by Hick (1950) and by Notterman and his colleagues (Mandriota, Mintz, & Notterman, 1962; Notterman, Cicala, & Page, 1960) among others. In general, these investigators found that the discrimination of differences in velocity does not follow Weber's law; that is, the just detectable increment in the velocity of a moving target is not a constant percentage of the velocity of the target. Rather, the difference threshold is at a minimum when the target moves with a velocity of between 1 and $2^\circ \cdot \sec^{-1}$, and is higher at both lower and higher velocities. This minimum varies from as little as 3–4% of the $1\text{-}2^\circ \cdot \sec^{-1}$ to as much as 15%, depending upon experimental circumstances. Of course, such results are valid only for comparisons of the velocities of small spots moving across a display at two different times, and it is difficult to generalize from them to other more complicated targets and backgrounds. Even so, a Weber ratio of about 12% provides a very rough index of sensitivity to differences in velocity, and it is of some interest that this difference threshold has not been used in testing the notion that the detection of acceleration is essentially a matter of comparison of velocity at two different times.

So one of the central concerns of researchers in this area is determining the degree to which the perceiver is sensitive to change of velocity (acceleration) per se. Section 1.3 reviews the experimental results obtained in this area.

1.2. Basic Concepts

So that the discussion in the following sections will be clear, let us define the basic terms used:

1. Uniform motion: the linear motion of an object or point at a single speed in a constant direction.
2. Velocity: a vector quantity (having magnitude and direction) indicating the speed of an object or point in a particular direction at a given moment in time (i.e., instantaneous velocity).
3. Speed: a scalar quantity indicating the magnitude of the velocity of a target regardless of its direction.
4. Acceleration: the rate of change of velocity.
5. Jerk: the rate of change of acceleration.
6. Circular motion: the motion of an object or point along a circular path.

The speed, velocity, or acceleration of a moving object (distal stimulus) need not be the same as the speed, velocity, or acceleration of the image of that object on the retina (proximal stimulus). All the foregoing definitions may be applied to the retinal stimulus as well as to the distal stimulus. Where needed, this distinction is made clear in the text.

1.3. Observations and Experimental Results

1.3.1. Natural Observations.

Science often begins with observations of natural occurrences that require explanation. This may lead to the reproduction of the observed phenomena in the laboratory, where hypotheses as to their causes may be tested under controlled experimental conditions. Although this is not necessarily the course of events leading to experimentation, it certainly is a major factor in influencing work in perception, where phenomena such as naturally occurring illusions may lead to scientific investigations.

Some observations of naturally occurring events are so common that they are often simply overlooked. For example, an object moving along a circular path is continually changing the direction of its motion. Hence by definition it is accelerating, and the acceleration (change in velocity) is perceived. Also, the increase in the rate of change of the area of a surface increases more rapidly as one gets closer to the surface. This too is a fairly common observation, and this acceleration in change of size is probably used as a cue in estimating stopping distance when braking one's automobile. However, it is not so obvious that one is sensitive to the change in speed of an object as it moves along a linear path. For if humans were highly sensitive to such a phenomenon, it would not have required the insight of Galileo to establish that falling objects move faster as they approach the center of the earth.

As already indicated, natural observations are often brought into the laboratory for further study. One example is the work of Michotte (1946), who wondered about the kinds of patterns of motion that lead to the impression that one of two moving objects may seem to cause the other object to move. He found that some kinds of nonuniform motion lead to such a perception, whereas other kinds of motion do not. "Causation" is perceived when one object moves toward the other and continues moving for a short period of time while the other object begins to move in the same direction (see Figure 19.2). It appears as though the motion of the first object is carried on by the second. Similarly, if an object moves toward a stationary object and, after reaching it, abruptly reverses its direction, the moving object has the appearance of having bounced off the stationary object. Although Michotte focused on the question of why one interprets some events as caused by others, he failed to consider the role of the higher derivatives of motion in producing these effects. In the case of perceived rebound, for example, there is a very rapid reversal of direction of motion. Such an event can be described as an abrupt change in velocity, which implies the presence of large second and third derivatives of motion. These higher derivatives affect the phenomenal quality of the motion.

Despite this apparent effect of nonuniformity on the perception of motion, doubt has been raised about the sensitivity of observers to acceleration. Levelt (Michotte, 1963), for example, noted that when a target moves from side to side in a simple harmonic manner, it is difficult to see any change in its speed except at the very ends of its transit. However, this "insensitivity" may well be due to the fact that the changes in speed are insufficiently strong.

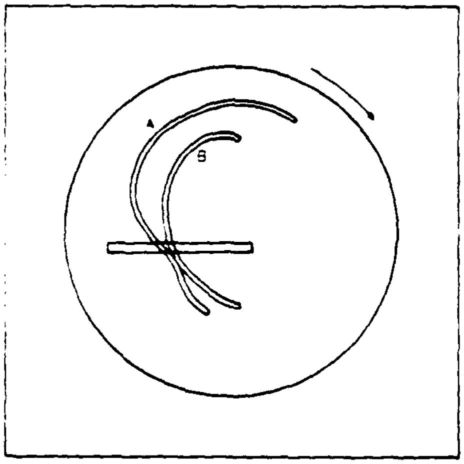


Figure 19.2. Michotte's apparatus. To produce perceived causality and related phenomena, Michotte (1946) utilized a disk on which lines similar to those shown in this figure were drawn. As the disk rotates in the clockwise direction, the lines visible in the slit are first seen as stationary. After a short time line A moves toward the center. When it reaches line B on its right, it continues to move at a slow velocity as the line to its right begins to move in the same direction. Shortly thereafter, the line on the left stops moving while the line on the right continues to move at a higher velocity. This produces the impression of "caused motion." If the line on the left had stopped moving before the onset of motion of the line to its right, then the two events would have been perceived as independent of each other.

The reader may perform a little experiment to test the validity of this point. If a sinusoidal signal of about 1 Hz is applied to one x-axis of a dual-beam oscilloscope, and a triangular function of the same fundamental frequency is applied to the other x-axis, two spots can be made to move from side to side on the face of the cathode-ray tube at the same fundamental frequency. It is immediately obvious that the spot moving as a triangular function of time seems to bounce back and forth from one end of its transit to the other, whereas the spot executing simple harmonic motion lacks the "bounce" and seems to slow up gradually at the ends of its transit. This difference in the perceived motion of the two spots could be due to the detection of the difference in the magnitudes of the higher derivatives of motion of the two spots. Alternatively, it could be mediated by an overshoot error that must occur when the eye tracks the target moving as a triangular function of time (see Mack, Chapter 17). Even so, there is a great need to obtain quantitative data to establish the degree to which individuals are sensitive to changing velocity.

Two-dimensional shadows of rotating three-dimensional wire objects may exhibit nonuniform motion, depending upon the shapes of the objects. In some cases these two-dimensional projections are perceived as rigid objects rotating in depth (Gibson & Gibson, 1957; Wallach & O'Connell, 1953). To explain these results, some experimenters focused on the transformations in the shape of the projections of three-dimensional objects onto the frontal plane; however, Ullman (1979) called attention to the important role of the change in speed of elements of the projection of a rotating three-dimensional object. These changes in speed do seem to play a significant role in perceiving the projected image as rigid and three-dimensional. More details are given by Sedgwick, Chapter 21.

The work of Johansson (1950, 1958, 1974) on the perceived organization of patterns of moving dots in the frontal plane and in depth includes several demonstrations in which nonuniform motion plays a role. This is amply treated by Mack, by Anstis, and by Pomerantz and Kubovy in Chapters 17, 16, and 36, respectively.

As already indicated, objects that move along circular paths must also be considered as exhibiting nonuniform motion, for the velocity of an object undergoing circular motion in the frontal plane is continually changing because its direction of motion is changing. In fact, an object moving at a constant speed v in a circle of radius r can be regarded as having an acceleration v^2/r directed toward the center of the circle. Some very interesting phenomena are associated with circular motion. Forms painted on a rotating disk, as shown in Figure 19.3, give rise to some surprising illusions (Musatti, 1924; Tauber & Kaufman, 1977; Wallach, Weisz, & Adams, 1956).

There is a tendency for position constancy to be lost for objects undergoing circular motion. This is in contrast with the perception of linear motion of objects in a normal illuminated environment, where the relative motions of the objects are perceived veridically, that is, in accord with the distal stimulus. However, with circular motion the perception tends to be in accord with the retinal motion of the objects. This is especially true of objects that are largely circular in shape (Wallach et al., 1956). Configurational factors strongly influence the resulting perception. The planetary motion experienced when an observer fixates one of the two circles on a rotating disk may disappear when this fixation is not maintained. As we shall see below, illusions that occur during circular motion can produce some interesting effects of motion in depth. Also, Matin, Boff,

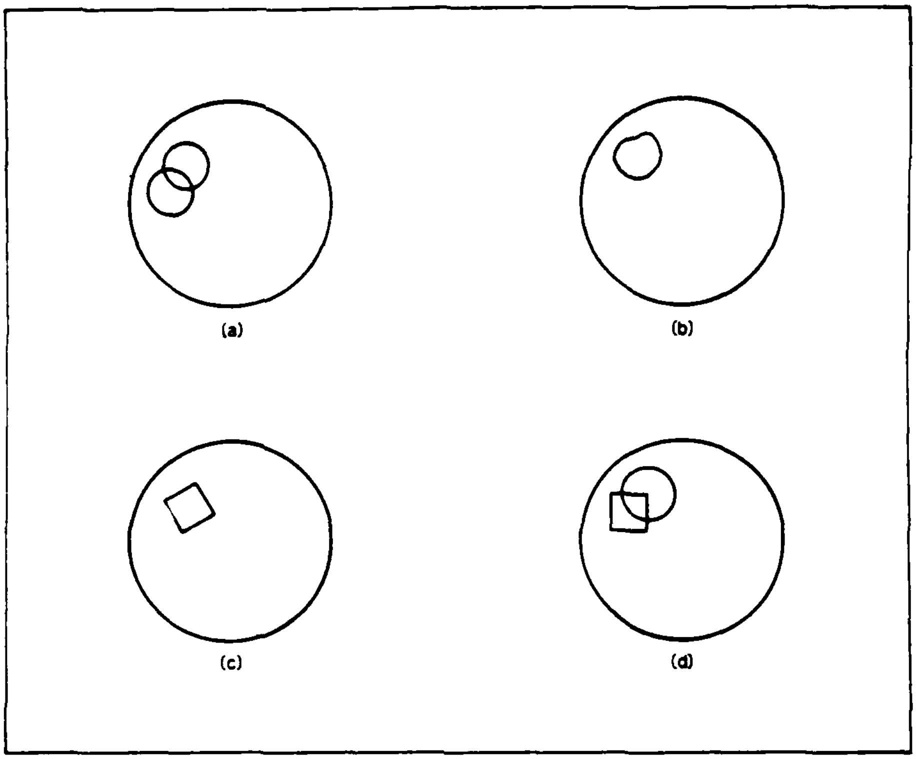


Figure 19.3. Some rotating figures. The eccentric intertwined circles in (a) rotate about the center of the disk, with one circle leading the other. However, when the disk rotates no faster than about 8 rpm, the observer generally reports that the two circles actually seem to execute a planetary motion, with one of the circles as the "sun" and the other the "planet" (Wallach, Weisz, & Adams, 1956). This effect has been found to occur when the eye of the observer moves to track one of the circles (Tauber & Kaufman, 1977), with the tracked circle seen as the sun and the other circle as the planet. A single circle containing a slight distortion (b) gives rise to the perception of a circle that remains "upright" during rotation of the disk, whereas the distorted portion independently "wobbles" around the circle (Wallach et al., 1956). The reason given for this is that circles have an inherently ambiguous orientation, that is, as a circle rotates about its center it undergoes no change at all. Because of this tendency to remain upright during rotation, the largely circular portion provides a frame of reference for the distorted segment, which moves around the "underlying" circle. A square, such as the one in (c), is unlike a circle because it has a determinate spatial orientation, and therefore it is seen as rotating as the disk turns. Tauber and Kaufman (1977) demonstrated that fixating one corner of a square on a rotating disk results in the perception of the square as turning about the fixated corner. This corresponds to the actual motion of the image of the square on the retina, just as the planetary motion of the intertwined circles is consistent with the motion of their images on the retina. Finally, when a square and a circle are intertwined, as in (d) fixation of the circle results in seeing the square rotate smoothly in planetary fashion about the circle. However, when fixation is switched to the square, the circle cannot be seen as rotating about the square, presumably because the unambiguous orientation of a square prevents the appearance of planetary motion.

and Pola (1976) and Boff (1978) observed that when a pair of collinear lines are rotated about their center, the upper line continuously appears offset from the lower line in the direction of rotation. This vernier offset is not fully understood (see further discussion in Chapter 16 by Anstis). Unfortunately, not enough is known about circular motion, because it has not been a popular research topic.

1.3.2. Experimental Results

1.3.2.1. Visually Guided Tracking of Accelerating Targets. We now turn to more formal experiments designed to elicit a clearer picture of the degree to which a person is sensitive to nonuniformity of motion. We begin with a visually guided manual tracking task, for it is reasonable to assume that the tracker must perceive the motion of the target if it is to be tracked accurately.

During a typical pursuit tracking task a target is made to move on a visual display, and the subject must use a joystick to keep a cursor aligned with the moving target. The difficulty of pursuit tracking is related to a number of factors, for example, vehicular dynamics (which is reflected in lag in response of the cursor relative to the tracking motion, etc.) and the speed and complexity of target motion. All these are reviewed in Chapter 39 by Wickens. For present purposes we consider only the complexity and speed of target motion and how these may affect accuracy of tracking.

The complexity and speed of target motion are commonly described in terms of its Fourier transform. It is relatively easy to track a target moving in a simple harmonic manner at a single low frequency. If the frequency is increased so that the target moves back and forth too fast for it to be followed, then performance obviously declines. When the target's motion includes several frequency components, or even when its motion can be described as a continuous spectrum of band-limited noise, tracking also becomes difficult, even at low frequencies.

This approach to tracking behavior implies the applicability of linear systems analysis to predict the performance of the human operator. Under the assumption that the operator can be described as a linear or quasilinear system, it is possible to determine the human's transfer function by having the operator track targets that move with different frequencies. The phase lag and attenuation of the tracking motion relative to the phase and amplitude of the target motion at each frequency fully characterize the operator's transfer function. Under the assumption of linearity (i.e., that the principle of superposition holds), it is possible to predict from the transfer function the accuracy of the operator's tracking behavior when confronted with target motions of any degree of complexity.

The foregoing approach is oversimplified because the operator rarely behaves as a linear system. Rather ingenious methods have been employed to predict operator tracking behavior despite evident nonlinearities (see Wickens, Chapter 39). For our purposes, it suffices to use this example to illustrate the way in which tracking performance, as measured in terms of its Fourier amplitude spectrum and its phase spectrum, can be evaluated in the frequency domain. This approach to motor performance is conceptually the same as current approaches to the study of sensitivity to spatial patterns and time varying stimuli (see Olzak and Thomas, Chapter 7, Ginsburg, Chapter 34, and Watson, Chapter 6).

To successfully track a target moving in a simple harmonic manner, the operator must be able to predict its future velocity. In fact, the velocity of such a target changes continuously over time. To keep pace with the target, the velocity of the cursor must be matched to that of the target. If the target is moving in a sinusoidal manner, its position at time t is $s = a \sin \omega t$, where a is the amplitude of the sine wave, ω is 2π times the frequency of the target in hertz, and ωt is the phase of the motion at t. Because phase can be measured from any arbitrary point in time, it is usually represented as $y = \omega t + p$. Now the velocity and acceleration are given by differentiation. Thus

$$s = a \sin(\omega t + p) \tag{1}$$

$$\frac{ds}{dt} = a\omega \cos(\omega t + p) \tag{2}$$

$$\frac{d^2s}{dt^2} = a\omega^2 \sin(\omega t + p) \tag{3}$$

As can be seen from Eq. (2), the velocity of the target is proportional to the product of its amplitude and frequency, whereas by Eq. (3) its acceleration is proportional to the product of the amplitude and the square of its frequency. Moreover, the phase of the acceleration lags that of the velocity by 90°.

To track a target moving in a sinusoidal manner, the operator must match a velocity that changes as a function of time. The amount of this change in velocity (the acceleration) increases rapidly with frequency. Therefore, one limiting factor governing tracking behavior may well be the rate at which the perceptual-motor system can sample and compare velocities.

It should now be obvious that the accuracy of visually guided tracking behavior depends on the way in which the operator processes the visual information, as well as the precision with which his or her motor system can respond to this information. According to one theory, the observer samples velocity in one interval of time and again in some other interval of time. If the two sampled velocities differ, then the operator infers that the target is accelerating. Alternatively, to account for the high accuracy with which operators learn to track simple harmonic motion, we may postulate an ability to extrapolate the rate of change in velocity integrated over short periods of time to allow the predictive behavior associated with successful tracking. Still another possibility is that operators simply generate a motor output at a particular frequency and adjust its phase and amplitude until the cursor being controlled matches the motion of the target; that is, operators minimize positional error, with no need to directly sense velocity or acceleration.

The foregoing discussion lays the groundwork for interpreting the results to be described in this section. Unfortunately, these results are somewhat meager, although they are highly suggestive.

Gottsdanker (1952) had a target move along the length of a horizontal slit at two different nonuniform speeds: positively accelerated with the velocity $v = 0.4t^2$ and negatively accelerated with $v = 16(5t)^{1/2}$. The uniformly moving and positively accelerating targets were visible for 10 sec whereas the negatively accelerating target was visible for 5 sec. In all cases the terminal velocity was 8 $\text{mm} \cdot \text{sec}^{-1}$.

The subject tracked the moving target with a pencil held in the slit and was asked to continue marking the projected path of the target even after it had disappeared. The continuous belt apparatus used to generate these stimuli is illustrated in Figure 19.4. Sample stimuli and tracks are shown in Figure 19.5.

The tracks made by these subjects suggest that they tended to follow the tangent to the target's motion at or near the time of its disappearance. They were clearly unable to project the acceleration of the target into its future, but they could predict the position of the target if it maintained the same velocity it had at the time of its disappearance. For negatively accelerated targets they were able to maintain the projected velocity with an accuracy of about 11% on the average. However, they departed from the target's actual path by tracking about 30% too fast. By contrast, the error in tracking the uniform target was no more than about 1%.

Averaging over subjects, the uniformly moving target was tracked at a rate of 7.92 $\text{mm} \cdot \text{sec}^{-1}$ (SD = 0.85). At the point of its disappearance the positively accelerating target had a physical velocity of 10.4 $\text{mm} \cdot \text{sec}^{-1}$. It was tracked after disappearance at a mean velocity of 6.97 $\text{mm} \cdot \text{sec}^{-1}$ (SD = 1.17). There was no significant difference between tracking velocity during the first second after disappearance and tracking velocity during the sixth second; that is, the target was tracked at a constant velocity. Gottsdanker concluded that tracking was based either on the velocity of the target at some time prior to its disappearance or on velocity integrated over a period of time prior to its disappearance. The subjects were unable to store and use information about the rate of change of the target's velocity prior to its disappearance.

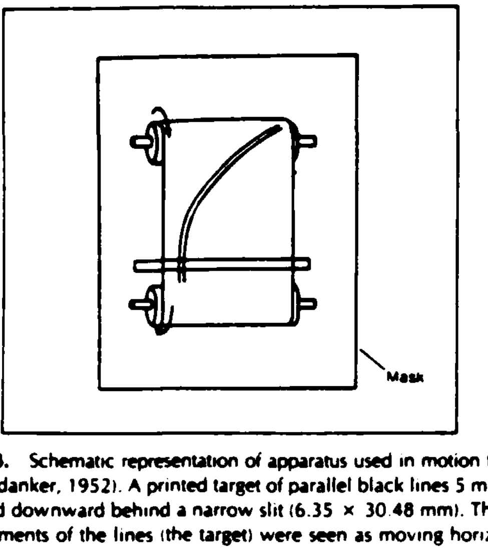


Figure 19.4. Schematic representation of apparatus used in motion tracking task (Gottsdanker, 1952). A printed target of parallel black lines 5 mm apart was moved downward behind a narrow slit (6.35 × 30.48 mm). The small visible segments of the lines (the target) were seen as moving horizontally across the length of the aperture in the mask. The speed of this motion was determined by the shapes of the lines. Line shapes generating positively accelerated, constant rate, and negatively accelerated motion were used. The velocity of the uniform motion and the terminal velocity of the nonuniform motion was 8 mm·sec^{-1}. (Unfortunately, Gottsdanker did not provide the stimulus dimensions in angular terms. If we assume a viewing distance of 50 cm, then the aperture was about 0.7° high by about 34° wide, and the terminal velocity was about 0.9°·sec^{-1}.) Subjects tracked the targets as they moved across the slit with a pencil held between the lines. In some trials the target disappeared before reaching the end of its transit, and subjects had to continue tracking the target at an appropriate speed.

Although this conclusion is valid for Gottsdanker's untrained subjects, it must be accepted with some circumspection. It is well known that the ability of a subject to track targets moving in a complicated manner improves significantly with training. For example, the visual-motor skills involved in shooting at moving targets improve considerably with practice. The skills developed by today's youngsters who play video games also testify to this conclusion. This kind of performance becomes quite automatic, suggesting that the higher derivatives are not responded to effectively when the performance is under cortical control. The question remains, however, as to whether acceleration is sensed or handled in some other way even when complex motion is successfully tracked.

1.3.2.2. Effect of Acceleration on Estimated Time to Collision. The phenomenological observations and the tracking study discussed above are complemented by a number of investigations based on more traditional psychophysical methods. These methods provide a more direct indication of the human's ability to detect changing velocity.

One useful technique in the study of motion perception is to have a subject estimate the future position of a target some time after it disappears. Estimation methods avoid dependence on motor skill, as in the tracking paradigm, and thus minimize the problem of effects of practice on performance.

In an experiment by Runeson (1975), one target (the standard) moved vertically along a 48° path. A "comparison" target moved horizontally across the display, beginning its transit 18° to the left of the vertical path and intercepting the path at its center. The edges of the display were blurred and several "landmarks" provided visual structure (see Fig. 19.6).

The velocity of the standard was always 9.6°·sec^{-1}. It should be noted that this is almost too fast to be seen clearly without eye movements (Kaufman, Cyrulnick, Kaplowitz, Melnick, & Stoff, 1971). The comparison target moved either with a uniform velocity or with a velocity described by the power function

$$s = kt^n \tag{4}$$

where s is the speed of the target, k is a scale factor chosen so that the average velocity is 9.6·sec^{-1}, and the exponent n defines the magnitude of acceleration at any time t. With $n = 1$ the motion is uniform. With $n < 1$ the target decelerates and with $n > 1$ the target accelerates. For example, when $n = 2$ the target exhibits a uniform acceleration and when $n = 1.6$ it exhibits a decreasing acceleration.

The onset of motion of the two targets differed from trial to trial so that the targets reached the point of intersection at different times. In addition, the target paths were partially occluded so that they disappeared before they crossed each other. The size of the mask was adjusted from trial to trial so that it occluded more or less of both target paths. The task of the subject was to judge whether the comparison target would reach the point of intersection before or after the standard ("same" judgments were not allowed).

Data were averaged to determine the point of subjective equality (PSE), or the point where the comparison target was judged equally often to be "ahead of" or "behind" the standard.

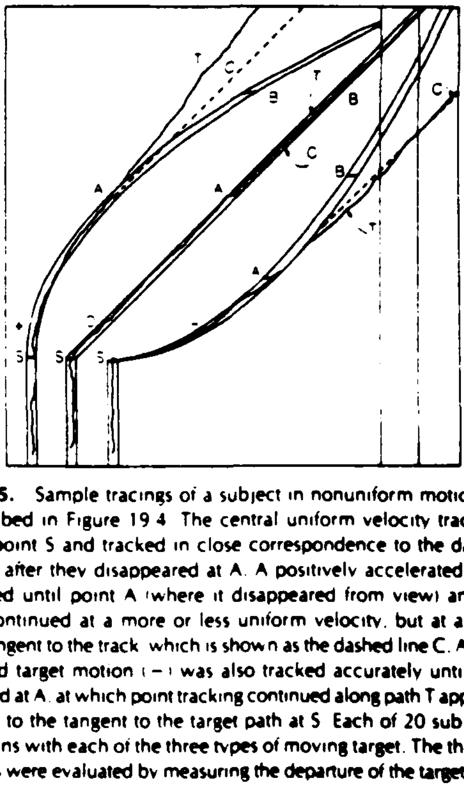


Figure 19.5. Sample tracings of a subject in nonuniform motion tracking task described in Figure 19.4. The central uniform velocity track (O) was begun at point S and tracked in close correspondence to the dark double lines even after they disappeared at A. A positively accelerated target (+) was tracked until point A (where it disappeared from view) and tracking along T continued at a more or less uniform velocity, but at a faster rate than the tangent to the track which is shown as the dashed line C. A negatively accelerated target motion (−) was also tracked accurately until the target disappeared at A, at which point tracking continued along path T approximately equivalent to the tangent to the target path at S. Each of 20 subjects had 8 tracking runs with each of the three types of moving target. The third through eighth runs were evaluated by measuring the departure of the target at intervals of 1 sec for 6 sec after the target disappeared. (Point B on all tracks represents the end of the 6-sec measurement period.) As illustrated by these tracings, subjects were unable accurately to predict accelerated or decelerated motion and instead tended to follow the tangent to the target's motion at or near the time of its disappearance. (From Gottsdanker, 1952.)

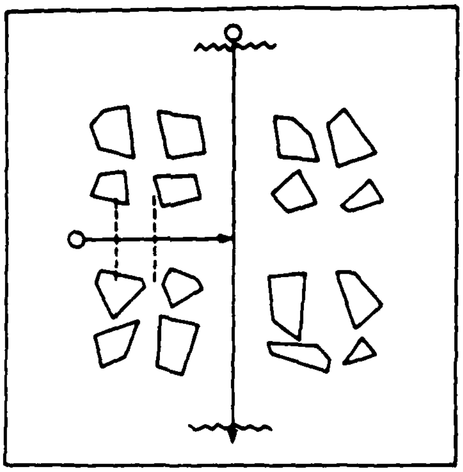


Figure 19.6. Schematic view of the display used by Runeson (1975) to study effects of different types of motion on estimated time to collision. Targets were bright blue rings 1.5° in diameter moving in a horizontal direction. A comparison stimulus moved from the top to the bottom of the display, as indicated by the vertical arrow, at a constant speed of $9.6^{\circ}\cdot\text{sec}^{-1}$. The ends of its 48° path were occluded by diffuse invisible screens (wavy lines). The target moved horizontally along an 18° path with an average velocity of $15^{\circ}\cdot\text{sec}^{-1}$. It was occluded by a sharp invisible edge after traversing one-fourth or one-half of its path (vertical dotted lines). Irregular shapes were placed on the surface of the screen to provide a frame of reference for the movement. The field outside the screen was dark. Subjects had to judge whether the target stimulus would arrive at the point of intersection before or after the comparison stimulus. (From S. Runeson, Visual prediction of collision with natural and nonnatural motion functions. *Perception and Psychophysics*, 1975, *18*. Reprinted with permission.)

Psychometric functions showing how the PSE varied with the kind of motion are shown in Figure 19.7.

When the comparison target moved at a uniform velocity of $15^{\circ}\cdot\text{sec}^{-1}$ and was occluded for all but one-fourth of its transit, the PSE departed from zero by −190 msec; that is, the targets were judged to arrive simultaneously when the comparison target arrived 190 msec after the standard. With late occlusion (one-half the track), the PSE was −43 msec, and did not differ significantly from zero. However, the PSE for the target with decreasing acceleration ($n = 1.6$) did not differ significantly from zero with either early or late occlusion. Large errors were observed for both the deceleration ($n = 0.7$) and uniformly accelerating ($n = 2$) comparison targets. Subjects showed a significant tendency to judge that a decelerating target collided with the standard when it actually lagged the standard. Conversely, the uniformly accelerating target was judged to lag the standard even though the two targets were actually on a collision course.

If subjects can sense or otherwise use the higher derivatives of these smoothly changing velocities, such errors should not occur. However, even in the case of uniform acceleration, where no higher terms (e.g., jerk) are needed for accurate prediction, there was considerable variability in performance. More important, variability was also high when both targets moved with uniform velocity; that is, there were no higher derivatives and there was no need to sense them to make predictions. Thus the targets may have been moving so fast that subjects used both the image-retina and eye-head systems to track one of them, thus producing highly nonuniform retinal motion. The better performance with the target moving with decreasing acceleration could be attributed partly to the fact that, during the latter portion of its transit, it had a velocity of about $4\text{–}5^{\circ}\cdot\text{sec}^{-1}$. This velocity is well within the range where the target is clearly perceptible as its image moves across the retina.

Although they are conjectural, the foregoing reservations illustrate a potentially important problem with studies such as this one by Runeson (1975). That is, the dynamic range of the velocity-sensing system based on motion across the retina is quite narrow. When velocities are higher than, say, $5\text{–}6^{\circ}\cdot\text{sec}^{-1}$ it may be impossible to "keep track" of the target (e.g., because of blur) as its image travels across a relatively small distance on the retina. At very slow uniform velocities ($< 5\text{–}6^{\circ}\cdot\text{sec}^{-1}$), on the other hand, prediction may become extremely accurate. Similarly, nonuniform motion may be evaluated to predict future position provided that the velocity of the target does not exceed some critical value. In short, it appears that many workers in this field may have used targets that moved too fast. This remains to be evaluated in future research.

One experiment whose outcome is consistent with this point of view is that of Rosenbaum (1975). In his study subjects judged when an occluded target would reach a fixed point in space. Subjective velocity was tacitly defined as the judged speed of the hidden target, the index of which was the time when the invisible target was assumed to intersect a visible stationary marker. Rosenbaum found that the distance over which the moving target was visible had no effect on accuracy. This led him to conclude that velocity per se was employed in making the judgment. Also, objective target velocity was highly correlated with subjective velocity; that is, it accounted for over 90% of the variance in subjective velocity. However, no other details were published so it is difficult to fully evaluate this report.

Rosenbaum provides more information on a second experiment which used moving targets accelerating at $7.97^{\circ}\cdot\text{sec}^{-2}$, $13.6^{\circ}\cdot\text{sec}^{-2}$, and $15.1^{\circ}\cdot\text{sec}^{-2}$. The six subjects had to judge how long after these accelerating targets disappeared they would reach a fixed visible marker.

Performance was best for the smallest of the three accelerations; in this condition the objective acceleration accounted for 85% of the variance in judged time to intersection. For the highest of the three accelerations, objective acceleration accounted for only 5% of the variance. Here performance was more nearly like that reported by Gottsdanker (1952). It is worth noting that subjects trained in physics did no better in this task than did "naive" subjects. Although the data are incomplete, they certainly force us to remain circumspect regarding any claims about the ability or inability of observers to sense acceleration.

1.3.2.3. ***Initial versus Terminal Velocity.*** One crude measure of sensitivity to acceleration is an observer's ability to judge correctly whether the velocity of a target at one point in time is the same or different from its velocity at another point in time. The ratio of velocity at time C_2 to velocity at time C_1 would be unity for a target moving with a uniform velocity, greater than 1 for a target increasing in speed, and less than 1 for a decelerating target.

Schmerler (1976) showed subjects a film of a target that emerged from a "tunnel" at one speed and then, after traversing a distance of 11.2°, entered another "tunnel" at the same or at a different speed. Target acceleration was 0, 2.3, 6.9, or $11.3^{\circ}\cdot\text{sec}^{-2}$. Running the films backward provided comparable values of deceleration. The lowest initial velocity was $1.4^{\circ}\cdot\text{sec}^{-1}$ and the highest $12.4^{\circ}\cdot\text{sec}^{-1}$.

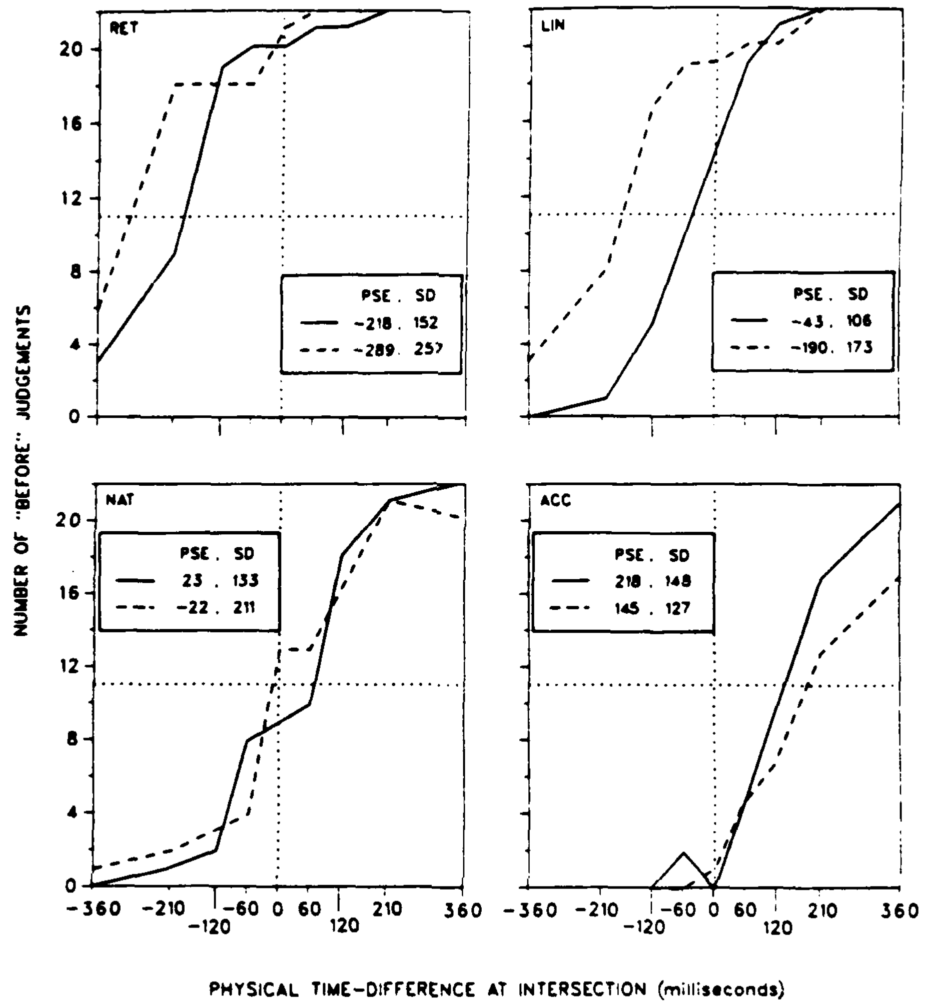


Figure 19.7. Effect of type of target motion on predictions of collision of targets traveling along partially occluded paths. Eleven subjects viewed the display shown in Figure 19.6 and judged whether a target moving with various degrees of acceleration would arrive at the point of intersection with a comparison (standard) stimulus before or after the standard. The number of trials on which the target was judged as arriving before the standard is plotted as a function of the physical time difference in their arrival at the intersection. Four kinds of target motion were used: RET—constant deceleration; LIN—constant velocity; NAT—"natural motion" (acceleration followed by a leveling to a constant velocity); ACC—constant acceleration. Broken and solid lines show results of early and late occlusion (see Figure 19.6). PSE (point of subjective equality) corresponds to the time difference at which the target and standard are estimated to have arrived simultaneously at the point of intersection. This PSE differed significantly from zero—that is, was either too early or too late relative to the objective time of intersection—for all but the motion with diminishing acceleration (NAT). Runeson concluded that the visual system does not utilize acceleration or deceleration in predicting motion but instead applies the stereotype of a "natural motion function." (From S. Runeson, Visual prediction of collision with natural and nonnatural motion functions. *Perception and Psychophysics*, 1975, *18*. Reprinted with permission.)

Only group thresholds were reported. In the case of acceleration, the threshold is defined as the terminal-to-initial velocity ratio at which the target was judged to be speeding up 50% of the time. The threshold for deceleration was determined in analogous fashion. Each of 60 subjects was given 12 trials for acceleration and 12 for deceleration.

Unfortunately, the results of this experiment are inconclusive because the threshold terminal-to-initial velocity ratios did not differ significantly across conditions even though the actual ratios presented varied by almost a factor of five. If all the subjects did not use the same criterion in making their judgments, the resulting grouped data were bound to be quite variable, and any changes in sensitivity to differences between initial and terminal velocity could have been masked when data were combined across subjects.

It may be of some interest to note that when the velocity near the end of an 11° traverse was approximately 2.7 times that near the beginning of the run, observers were likely to judge that the target had speeded up. Thus sensitivity to acceleration was unaffected by an increase in average velocity, although the data are too noisy to state this as a firm conclusion.

Discrimination between terminal and initial velocity improved when the target passed through a third tunnel placed midway between the two end tunnels, thus interrupting the appearance of the target. This result is consistent with the view that the subject senses velocity at one time and compares it with velocity sensed at another time. This is supported by experiments in which other criteria are employed, as described in the following section.

1.3.2.4. Direct Comparisons. Runeson (1974) investigated the question of how well subjects can judge the difference between uniform and nonuniform motion. In this experiment a target moved horizontally along a track subtending 48° at the observer's eye. The motion had either a uniform velocity or one of three nonuniform velocities described by the power function given in Eq. (4). In this case, however, the scale factor k was chosen so that the average velocity was $48° \cdot \mathrm{sec}^{-1}$.

In this particular experiment subjects viewed a target that moved across the screen twice. Their task was to judge on which of the two presentations the target moved with uniform velocity. In fact, the target that moved with a constant velocity appeared to subjects to be moving with a nonuniform speed. The target they judged to be moving with uniform velocity actually moved with decreasing acceleration (i.e., with $n = 1.3$ or 1.6). To appear as constant, a target must begin its motion with a certain amount of acceleration which later falls off to a nearly constant velocity. Runeson called this "natural motion," because it is typical of naturally occurring horizontal motions of objects influenced by the drag of a medium that causes them to slow down.

This explanation is not entirely convincing, despite its apparent "ecological" validity. For one thing, it is well known that sensitivity to motion is greater when a moving target is close to an edge than when the target is far from edges and in an empty visual field. Therefore, the motion of the target used by Runeson is not strictly accounted for by its physical velocity and acceleration, simply because the perception of its speed at any instant may well be affected by its position in the display. In fact, none of the studies described here has incorporated factors such as proximity to the edges of a display in their treatment of perception of acceleration. Also, the average velocity of $48° \cdot \mathrm{sec}^{-1}$ used in this experiment by Runeson is extremely high. It is unlikely that a target moving so fast can be seen clearly unless the eye moves to track it (Kaufman et al., 1971). Second, Runeson's results illustrate a subtle point about the reported appearance of motion. That is, if we accept Runeson's results at face value, they actually imply that observers can discriminate between uniform and nonuniform motion, except that they misname the two kinds of motion. Thus the observers can discriminate between objects moving with decreasing acceleration and those moving at a constant velocity. If these observers had been given feedback, they might well have come to label the different kinds of motion correctly. Once again, we must conclude that when higher derivatives of motion are present, they often have an effect on the appearance of the stimulus as described by the subject. This still leaves open the question of whether acceleration is perceived directly or is inferred from the sampling of velocities at different times.

Gottsdanker, Frick, and Lockard (1961) performed an experiment similar to Runeson's, in which they reached the conclusion that acceleration is not sensed directly. In their study, 160 college students were given 100 trials each in which they viewed consecutive runs of a moving target. Each trial contained two runs. The target moved with a constant velocity on one run and with an accelerating or decelerating motion on the other. The subject had to tell on which run the motion was constant. Because this method is much less criterion-sensitive, some of the problems associated with Schmerler's (1976) study are avoided.

The velocity of the target ranged from 0.96 to $15.4° \cdot \mathrm{sec}^{-1}$, and acceleration ranged from 0.26 to $67.6° \cdot \mathrm{sec}^{-2}$. Presentation time varied from 0.45 to 3.6 sec. Because the stimuli were presented via motion pictures, playing the film backward gave decelerating stimuli. Unlike Schmerler (1976), Gottsdanker et al. (1961) found that sensitivity to acceleration decreased as mean velocity was increased. They also found sensitivity to be adversely affected by decreasing presentation time. Finally, the ability to discriminate acceleration from uniform velocity is affected more by the total change in velocity than by the duration of the stimulus. This supports the view that subjects compare early and late velocities. The minimum detectable accelerations are associated with stimuli whose initial and terminal velocities differ by as little as 26% and as much as 157%, depending upon the stimulus conditions. These values are quite a bit larger than any reported by Notterman and his colleagues, as described in Section 1.1, and much smaller than those observed by Schmerler. Of course, subjects may have been making their judgments on the basis of changes in velocity that were actually smaller than these terminal values.

1.3.3. Summary. It is obvious that none of the studies discussed thus far in this chapter allows a definitive statement concerning human sensitivity to acceleration, differences in velocity, or the mechanisms that may make it possible to detect either differences in velocity or any of the higher derivatives of motion. For one thing, the parameters of the various experiments may not have been appropriate; for example, the velocities employed were frequently too fast (e.g., Kaufman et al., 1971). Often there was no consideration of or adequate control for the abrupt onsets and offsets of motion, the effect of the presence of a framework (Brown, 1931), target size, luminance contrast, and other factors (e.g., Kaufman & Williamson, in press). Effects of differences in criteria were not considered either. Even so, all of this prior work is instructive in the sense that it makes it possible to conduct experiments in which the range of velocities is appropriate, and it helps to define the methods and stimuli that would lead to more general conclusions. All these considerations led to one recent parametric study.

1.4. Parametric Study

Kaufman and Williamson (in press) reported an experiment designed to overcome some of the problems described above. Rather than the moving spots used by previous investigators, stimuli were computer-generated gratings produced by sinusoidally modulating the luminance of a raster on the screen of an oscilloscope. These gratings had one of three different spatial frequencies, 0.5, 2.0, or 4.5 cycles per degree. The average luminance was the same for all gratings and was set at $40\ \mathrm{cd} \cdot \mathrm{m}^{-2}$. The luminance contrast of each grating had one of two values, 0.2 or 0.5 (see Ginsburg, Chapter 34). The gratings drifted across the display at one of three different average velocities—0.5, 2.0, or $5.0° \cdot \mathrm{sec}^{-1}$—and thus they were in the range of the velocity-sensing capabilities of the image-retina system. The direction of motion was either to the left or to the right, and was varied at random from trial to trial to prevent adaptation to a given direction. To introduce acceleration, the speed of the grating was sinusoidally modulated at a frequency of 1, 2, 4, or 6 Hz. Sensitivity to this acceleration was measured by determining a threshold for the amount of modulation of speed needed for its detection as a function of all the foregoing parameters (luminance contrast, spatial frequency, average speed, frequency of modulation of speed, and direction of motion).

The thresholds (75%) were determined by means of a modified staircase method (see Falmagne, Chapter 1), in which the subject had to decide which of two presentations of the same spatial frequency or average velocity, for example, included a modulation of speed. This two-interval forced-choice procedure is criterion-free.

It is instructive to evaluate the data of this experiment in two different ways. First, by analogy with the Michelson contrast used to describe the luminance contrasts of grating stimuli, the thresholds can be expressed as the difference between the maximum and minimum velocities at threshold, divided by their sum. This is essentially the same as a Weber ratio. The main findings were that sensitivity to the acceleration was significantly related to the average velocity of the grating. On the average, the threshold for detecting the modulation was at a minimum (12%) when the average velocity was $2°\cdot\sec^{-1}$, and was significantly greater at lower and higher average velocities. At velocities above $5°\cdot\sec^{-1}$, the higher spatial frequency patterns could not be resolved by a subject fixating a point in the center of the screen, so changes in speed of gratings moving at or above this average speed could not be detected at all. For lower average velocities, the lowest threshold is in the vicinity of $1–3°\cdot\sec^{-1}$. The other main effect was that of modulation frequency. Here too there was evidence for "tuning" in the sense that the threshold was lowest (17%) when the modulation frequency was 2 Hz, and greater at lower and higher modulation frequencies. Finally, the threshold was significantly lower for the higher spatial frequencies than it was for the lowest spatial frequency, varying from 24 to about 18%. There were no main effects of direction of motion or of luminance contrast.

Although thresholds for detecting changing speed are not a constant percentage of average velocity, there is evidence of a shift in magnitude of the threshold level in the direction predicted by Weber's law. Thus the threshold expressed as the absolute amplitude of the change in velocity is nearly proportional to average velocity for each modulation frequency. It is of some interest to note that the detectable increment in velocity varies from about 7.5 min $\text{arc}\cdot\sec^{-1}$ for the lower average velocity to as much as $1.8°\cdot\sec^{-1}$ for the highest. Thus the lowest threshold (expressed as a difference in velocity) is only about twice the magnitude of the absolute threshold for motion, which, in a structured visual field, is on the order of 3 min $\text{arc}\cdot\sec^{-1}$.

There are other ways in which to express the results of this study. For example, it is possible to describe a stimulus like a moving grating in terms of the temporal frequency with which a point on the retina is stimulated by alternating levels of luminance. In fact, the temporal frequency of stimulation is the product of the average velocity and the spatial frequency of the stimulus. If this were a higher-order variable to which the subject responded, then it could be claimed that the results are not due to some sensitivity to velocity and to velocity change but rather to a change in temporal frequency—a kind of frequency modulation of a pattern. However, Kaufman and Williamson (in press) analyzed their data in terms of temporal frequency and found a highly nonuniform relationship between temporal frequency and threshold. The analysis suggested that the main effect was of average velocity, and this contributed 56% of the variance in the data. Clearly, more data are needed to fully explore the parameters that affect sensitivity to changing velocity.

1.5. Conclusions

The various experiments described in this chapter thus far are not necessarily inconsistent with each other. For example, Gottsdanker's (1952) early finding that subjects track at or near the terminal velocity of a target after it disappears from view might have been because subjects were tracking at high velocities and therefore had too little time to observe the target and could not respond to the change in velocity per se. The demonstration by Kaufman and Williamson (in press) of sensitivity to changing velocity may have been due to the fact that subjects had ample time to view the pattern as it moved, and the fact that the motion did not have a definable onset or offset. Also, the conditions under which such sensitivity could be demonstrated were confined to a rather narrow range of temporal and spatial parameters. These parameters simply were not sampled in the experiments by Runeson (1975) or any of the others discussed here.

In a way, the fact that one is sensitive to acceleration only over a narrow range of velocities, temporal frequencies, and spatial frequencies does make adaptive sense. If the visual system were capable of sensing acceleration, regardless of velocity or other parameters, the amount of neural circuitry involved would be enormous. By narrowing the range of conditions under which detection of changes in velocity is possible, the requirements placed on the organism are similarly narrowed. Also, if the image-retina system detects acceleration, it should do so only when it is capable of resolving moving objects. If the object is moving very fast, then it can be tracked with the moving eye, and if the eye should start to lag or lead the tracked target, the resulting change in the velocity of its image should also be detected if the error in tracking is to be corrected. Hence the visual system should be better suited for detecting changes in the velocity of objects whose images move relatively slowly on the retina. At the same time, the visual system may well tolerate slight changes in the speed of images that move very slowly on the retina, because such images correspond to targets that are already being tracked fairly well. The fact that the visual system is somewhat less sensitive to changing velocity of very low spatial frequencies is also an interesting finding, because it is consistent with the notion that such sensitivity is an attribute of central vision rather than of the peripheral retina. However, this and other issues remain for future investigation.

1.6. Key References

An excellent review of the older literature on acceleration is given by Gottsdanker (1956), who begins with the complication experiment of Bessel and its application by Wundt to the study of the perception of acceleration of the pendulum bob (Boring, 1950). He goes on to discuss the problem of measuring thresholds for sudden changes in velocity, his own impressive contributions to this literature, and the relevant work of Metzger (1953) and Johansson (1950).

The most recent key publication is by Schmerler (1976); his article goes over some of the ground already covered by Gottsdanker and brings us up to date. Apparently Schmerler did not have access to the paper by Rosenbaum, which appeared in 1975. The latter author comes to conclusions opposed to those of Gottsdanker and Schmerler.

2. MOTION IN DEPTH

2.1. Background

Animals and humans, including infants, tend to avoid objects that approach them rapidly. Rapid changes in angular size ("looming") and changes in textural density of surfaces lead to avoidance reactions or some other behavior indicating that the object is perceived as drawing near (Ball & Tronick, 1971; Bower, Broughton, & Moore, 1970; Fishman & Tallarico, 1961; Hayes & Saiff, 1967; Regan & Beverley, 1978a, 1978b; Schiff, 1965; Schiff, Caviness, & Gibson, 1962; Schiff & Detwiler, 1979; Tronick, 1967; Wheatstone, 1852). Similar changes in angular size and in texture of physically stationary surfaces may aid the locomoting observer toward an object or point on a surface (Gibson, 1950, 1957, 1958; Gibson, Olum, & Rosenblatt, 1955; Lee, 1974; Regan & Beverley, 1979b, 1982).

This section emphasizes the changing of size and of textural density as objects approach observers and as observers approach objects and surfaces. Because so little information exists concerning how extravisual information interacts with visual information, it is not dwelt on here.

Information other than changing size and texture is available to an observer moving relative to objects and surfaces. For example, the amount of visible texture occluded by an object at right angles to a textured surface changes in proportion to the square of the distance to the object (Gillam, 1981). Also, objects that are relatively nearby form disparate images on the two retinas when a distant point is fixated. The amount of this disparity changes as the object approaches or recedes. Thus binocular disparity may also play a role in perceiving changes in depth. Similarly, both accommodation and convergence may covary with slow changes in distance to a fixated object.

There are two kinds of changes in depth. One is the change in distance between an observer and an object. The other is the change in distance between two objects along the observer's line of sight. This corresponds to the distinction between "egocentric" and "exocentric" described in Chapter 16 by Anstis and Chapter 17 by Mack. We consider both kinds of motion here, but our main focus is on egocentric changes in depth.

It is important to recognize that an object may be perceived as moving in depth even though it is undergoing no physical motion in depth. As long ago as 1852, Wheatstone reported that, when the magnification of an object's retinal image changes, observers have the impression that the object is moving in depth. Thus changing size alone can be sufficient to produce an impression of motion in depth. The kinetic depth effect (KDE) in a shadowgraph is a second example (Wallach & O'Connell, 1953). As illustrated in Chapter 22 by Hochberg, this fact is exploited in film and television. Also, an observer may move through an environment so that objects in that environment are displaced toward him or away from him. Yet the observer may perceive himself as moving and the objects as stationary. Thus "motion in depth" is a phrase that covers object motion, illusory object motion, real self-motion, and illusory self-motion. The usage of the term "motion in depth" will be made explicit in the context in which the phrase is used.

2.2. Experimental Results

2.2.1. Phenomenological Data. Section 1.3.1 described the planetary motion often perceived when two circles painted on a flat disk are rotated (see Rock, Chapter 33). As illustrated in Figure 19.3, planetary motion is perceived when the eye fixates one of the circles as it rotates about the center of the disk. This is not the only perceptual consequence of viewing such stimuli, however. When a small circle is drawn inside a larger circle, as illustrated in Figure 19.8, the resulting perception may take several forms. One is a depth effect in which the observer perceives a solid truncated cone with either its apex or its base nearer the observer. The cone has a nutating motion; that is, its nearer portion appears to wobble as the entire cone moves along its circular path. Wallach et al. (1956) attribute this phenomenon to the classic kinetic depth effect (KDE), because the relative motions of the retinal images of the two circles satisfy the conditions for perceiving a moving two-dimensional image as a rigid object in depth. The KDE and other depth effects related to motion parallax are described in Chapter 21 by Sedgwick and Chapter 22 by Hochberg.

The depth effect described above illustrates that changing image size is not a necessary condition for the perception of motion in depth. Even when objects do not move, there is a tendency to see the larger of two otherwise identical objects as nearer (Epstein, 1963; Gogel, Hartman, & Harker, 1957; Hochberg & Hochberg, 1952; Ittelson, 1951). The question addressed next is the degree to which changing size provides a reliable basis for accurately judging the motion of objects in depth in both simple and complicated visual settings.

2.2.2. "Looming" or Changing Size

2.2.2.1. Visual Sensitivity to Changing Size. As an object draws nearer to an observer, its boundaries expand away from each other. Regan and Beverley (1978a) investigated whether the visual system is specifically sensitive to changing size or whether sensitivity to changing size can be reduced to sensitivity to motion per se. In brief, they demonstrated a specific sensitivity to looming.

In their experiments subjects viewed bright squares on a dimmer background. The edges of the squares moved in one of two different ways. In the inphase condition the opposite edges of the square moved in phase with each other so that the whole

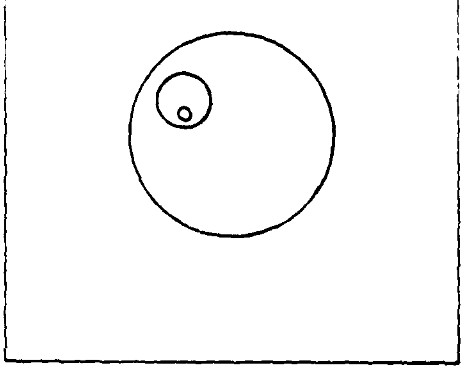


Figure 19.8. The stereokinetic effect. A large circle painted on a disk and containing a smaller eccentrically located circle may appear as a solid cone executing a nutating motion as the disk rotates about its center. The smaller circle appears to wobble about the inner circumference of the larger circle when fixation is on a point on the rim of the larger circle. The appearance of the pattern as a depthful truncated cone is attributed by Wallach et al. (1956) to the classic kinetic depth effect.

square moved along a diagonal path without changing size. In the antiphase condition the edges moved in opposite directions and the square's size oscillated. The reason for selecting these two stimuli was that motion stimulation was identical in the two cases: local motion detectors would merely "see" any given edge moving from side to side. The difference between the two stimuli was that, at any given instant, opposite edges moved either in the same direction (inphase) or in opposite directions (antiphase). This is illustrated in Figure 19.9(a).

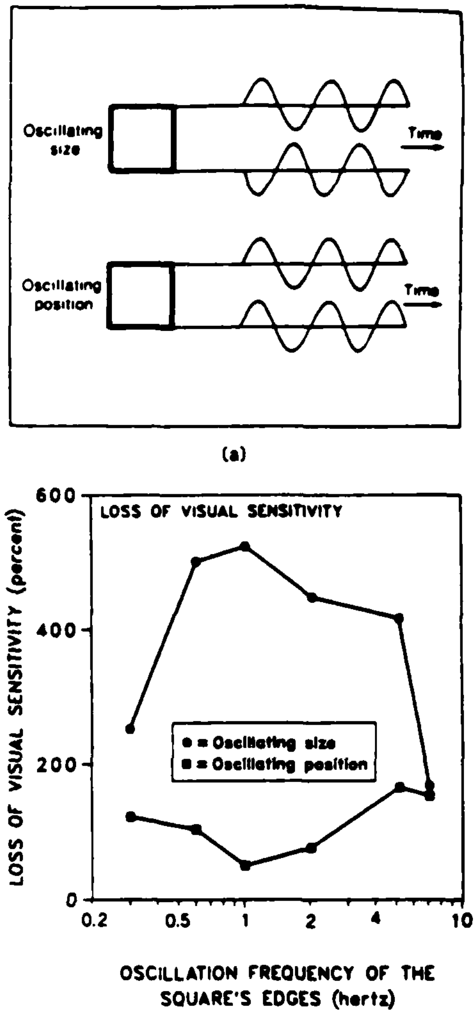
The smallest detectable oscillation amplitude was measured for inphase test oscillation and for antiphase oscillation using the method of adjustment. The subjects then inspected a strong antiphase oscillation for 25 min and the two thresholds were measured again. Figure 19.9(b) shows that this resulted in an appreciable loss of visual sensitivity to oscillating size. However, sensitivity to the inphase oscillation was only slightly affected. Because motion stimulation was the same for inphase and antiphase test stimuli, the difference must have been due to some other factor, and it was proposed that the visual pathway is specifically sensitive to the *difference* between the retinal velocities at two retinal locations. When the experiment was repeated by having the subject inspect an inphase oscillation, visual sensitivity was hardly affected at all either for the inphase or the antiphase test oscillations. In the latter case, adaptation could only have been due to motion per se and not to changing size. The relative weakness of this adaptation can be attributed to the fact that the motion was oscillatory and that few contours were present. The stronger aftereffects of motion, such as the waterfall illusion, occur only with exposure to unidirectional motion which, in addition, involves stimulation by many moving contours. The fact that threshold elevation for looming was larger (up to 500%) in the antiphase adaptation condition than in the inphase condition suggests that in this case subjects were adapting to looming and not to motion of the edges of the square, and that looming adaptation can be induced by much weaker stimuli than is required to induce classical motion adaptation.

Changing luminance could not account for the aftereffect described above because flickering a stationary square produced no appreciable adaptation. Furthermore, similar looming adaptation was obtained when the adapting stimulus was a bright square on a dark background and the test stimulus a dark square on a bright background (Regan & Beverley, 1978a). In point of fact, stimulus contrast has little influence on looming adaptation, provided that the stimulus is clearly visible (Petersik, Beverley, & Regan, 1981).

The experiments just described were limited to only two directions of motion: motion parallel to the frontal plane (inphase oscillation) and motion along the line of sight (antiphase oscillation, or looming). However, both kinds of motion may be superimposed on each other, as when an object moves along a slanted path toward the observer. Such motion has an inphase component as well as an antiphase component. Regan and Beverley (1980b) used a wide range of object trajectories to discover if the hypothesized looming system (Regan & Beverley, 1978b) is independent of the moving object's trajectory. The rationale is illustrated in Figure 19.10(a)–(c).

If looming adaptation were unaffected by added frontal plane motion (inphase oscillation), then all adaptation trajectories should have produced the same antiphase threshold elevation. Figure 19.10(d) shows that this prediction was verified within an accuracy of ±5% over a wide range of trajectories.

These findings are consistent with the view that the visual system contains functional subunits or "channels" for looming that operate as illustrated in Figure 19.11. As shown in the figure, motion-sensitive filters supply velocity signals (x and y) to a hypothetical changing size filter whose output is proportional to the algebraic difference between x and y (the velocities of widely separated edges). It is a striking finding that the visual system computes this difference to a high precision that is almost independent of the absolute values of x and y [Figure 19.10(d)].



(b)

Figure 19.9. Specific threshold elevation due to adaptation to changing size. Stimulus conditions used are illustrated in (a). Solid squares (mean side length = 0.5°) were shown in two modes of motion. In one (oscillating size), parallel edges of the square moved toward and away from each other in a periodic manner. This oscillatory antiphase motion of the edges is shown for two sides only, but the square was actually increasing and decreasing in size. In the other mode, opposite edges oscillated in phase with each other (oscillating position) so that the square's position shifted. This changing position occurred along a diagonal path, because all four edges of the square were moving. As shown in (b), after 25 min of adaptation to a strong (6 min of arc peak to peak) 2 Hz oscillation in size, visual threshold for changing size was elevated about 500%, whereas threshold for inphase oscillation showed little change. Adaptation to a 6 min arc inphase oscillation and adaptation to a flickering stationary square had little effect on sensitivity to changing size. This effect was also independent of the amount or direction of contrast of the adapting square, which could be different from that of the test square. (From D. Regan & K. I. Beverley, Looming detectors in the human visual pathway, *Vision Research*, 1978, *18*. Reprinted with permission.)

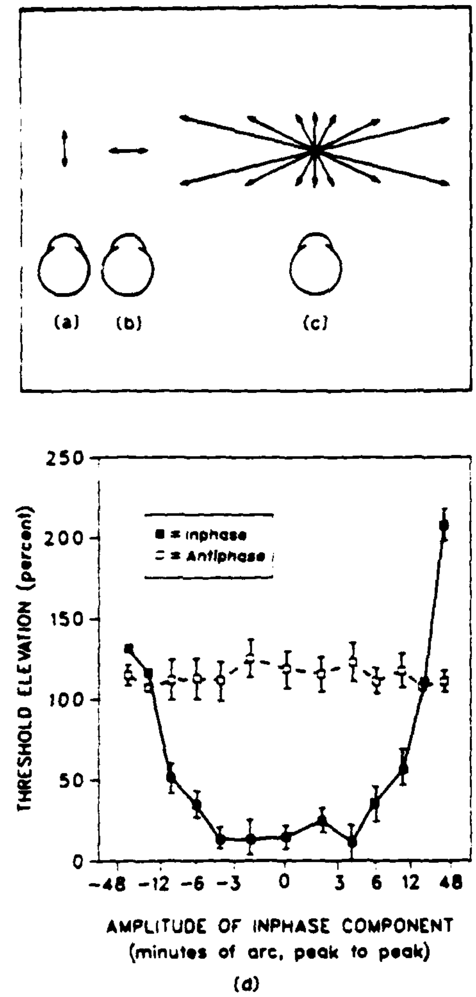


Figure 19.10. Independence of adaptation to changing size and adaptation to changing position. A target moving directly toward and away from the eye is shown in (a), and a target moving left and right in the frontal plane is shown in (b). A target moving as in (a) would change in size, whereas one moving as in (b) would change in position. Both kinds of motion may be combined, as in (c), to produce several trajectories. Regan and Beverley (1980b) used targets with 11 different trajectories to determine if adaptation to changing size is independent of adaptation to changing lateral position. Stimuli were bright squares 0.5° on a side. Targets at all trajectories had the same antiphase (changing size) component; that is, the component of motion toward and away from the observer was the same, but the component in the frontal plane (the inphase component) differed, depending on the trajectory. The graph in (d) shows how the thresholds for pure inphase motion and pure antiphase motion were affected after adaptation to stimuli at each trajectory. Elevation of antiphase thresholds was independent of the amount of inphase motion, whereas inphase threshold elevation progressively increased with the amplitude of the inphase component. (From D. Regan & K. I. Beverley, Visual responses to changing size and to sideways motion for different *directions of motion in depth*: Linearization of visual responses, *Journal of the Optical Society of America*, 1980, *70*. Reprinted with permission.)

These findings imply that the visual system directly responds to the line of sight component of an object's velocity independently of its velocity in the frontal plane. Regan and Beverley's experiments were restricted to the case of an object moving in relation to a stationary observer. The possible roles of head and eye movements have yet to be formally studied in situations such as those described above.

There are interesting hints about the possible effects of eye and head movements, however. For the case of motion in depth along a line through the eye, the absolute amount of looming adaptation was about the same when the retinal image was stabilized and when it was unstabilized as in the experiment shown in Figure 19.9 (Regan & Beverley, 1978b). However, the situation seems to be very different when trajectory is varied as shown in Figure 19.10(d). The data in Figure 19.10(d) were obtained when the stimulus was slightly "jittered," mimicking the amount of retinal image jitter associated with free head movements. Without this jitter the looming channels seem to be much less independent *of trajectory*. Thus it seems that the motion "noise" introduced by free head and eye movements is essential for independent operation of the looming channels (Regan & Beverley, 1980a).

2.2.2.2. Temporal Tuning of Changing-Size Channels. At first sight, Figure 19.9 suggests that the hypothetical looming channels are most sensitive over a frequency range of about 0.6–4.0 Hz. However, in this experiment, the adaptation frequency had a single value of 2.0 Hz. To resolve this point, the experiment was repeated with adaptation oscillation frequencies ranging from 0.25 to 24 Hz. The peak of threshold elevation was found to vary with adaptation frequency. This result is consistent with a multiplicity of looming channels tuned to different temporal frequencies of oscillation (Regan & Beverley, 1980b).

Searching for a physiological basis for specific sensitivity to looming, Regan and Cynader (1979) studied 108 neurons in area 18 of the cat's visual cortex. Almost all responded to changes in stimulus size. Control experiments, however, showed that most of these neurons were *sensitive to the changes* in total light flux that accompanied size changes. Only two units were shown to respond specifically to changing size. The response was similar whether the bar was brighter or darker than its surroundings and also when the bar was placed in widely separated portions of the visual field. However, an appreciable proportion of the neural population responded more strongly to expansion or *contraction* of width than was predicted by the responses to motion of a single edge. Thus whereas very few units are sharply tuned to changing size per se, the statistical

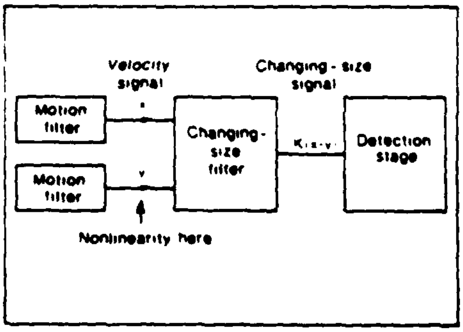


Figure 19.11. Model of changing-size channels. This model, based on psychophysical evidence (Regan & Beverley, 1980b, 1981), includes three stages. The first is a set of motion-sensitive elements ("motion filters") that supply velocity signals (labeled x and y) to a hypothetical changing-size filter whose output is proportional to the difference between x and y (the velocities of widely separated edges). The output of the changing-size filter is fed to a threshold detection stage. (From D. Regan & K. I. Beverley, Motion sensitivity measured by a psychophysical linearizing technique. *Journal of the Optical Society of America*, 1981, *71*. *Reprinted with permission.*)

distribution of the activity across a large population of neurons may be involved in the organism's sensitivity to changing size.

2.2.2.3. Nonlinear Aspects of Looming Sensitivity. As mentioned above, when head and eye movements are small, so that the jitter of the retinal image is correspondingly low, this nonlinearity causes the output of the changing-size channel to be erroneously low for objects with trajectories that just graze the eye (Regan & Beverley, 1980a). Under such conditions, a subject would underestimate the motion in depth (i.e., would underestimate the component of the velocity vector along the line of sight). However, in daily life free head motion produces appreciable image jitter, which has the effect of "linearizing" the system. In a nonlinear system whose output frequency in response to a sinusoidal input is twice that of the input, the addition of substantial high-frequency jitter to the input results in an output at the fundamental frequency of the input. The reasons for this are described by Spekreijse and Reits (1982), and at an elementary level by Kaufman (1974). Thus adding jitter to antiphase oscillation of the square linearizes the system, and this effect can be used in analyzing the dynamic properties of the changing-size channel in Figure 19.11 as described below.

Threshold elevations were produced by adaptation to changing-size oscillation of a given temporal frequency. The effects of head motion were mimicked by adding auxiliary "jitter" oscillations of different frequencies to the changing-size oscillation. The frequency and amplitude of the auxiliary oscillation were adjusted to produce a constant linearizing effect (Regan & Beverley, 1981). In this way it was shown that (1) the first stage of the changing-size channel behaves linearly, and nonlinearity is introduced after the first stage; and (2) the high-frequency attenuation in the first stage roughly accounts for the high-frequency attenuation for the whole channel.

2.2.2.4. Time to Collision. Astrophysicist Fred Hoyle, in his science fiction novel *The Black Cloud* (1957), seems to have been the first to point out that the time to collision with an approaching object is given by $(\theta/\dot{\theta})$, where $\dot{\theta}$ is the object's angular size and θ is its rate of increase of angular size at any given instant. This relation can be understood as follows. Suppose that an object's absolute width is S and its distance is d at time t, and that its distance has decreased to $(d - \Delta d)$ at time $(t + \Delta t)$. The change in its angular size is given by $\Delta\theta = S/(d - \Delta d) - (S/d) = (S\Delta d/d^2)$ approximately. Dividing both sides by Δt, we have $\dot{\theta} = \Delta\theta/\Delta t = S/d^2 \times \Delta d/\Delta t$. If the velocity toward the eye remains constant and the object does not rotate, then the time to collision is given by $d/(\Delta d/\Delta t) = \theta/\dot{\theta}$, because $\theta = S/d$. In words, time to collision = (angular size at any given instant)/(instantaneous rate of change of angular size). This formula is given added physiological interest by the finding that the human visual system is specifically sensitive to the rate of change of size ($\dot{\theta}$), and may contain a neural mechanism sensitive to $\dot{\theta}$.

Although in Hoyle's novel the calculation was of the time to collision with a black cloud approaching the earth from outside the solar system, the formula applies equally well to earthbound events, and is involved in a model of anticipatory braking by automobile drivers in traffic. Lee (1976, 1980) points out that drivers do not normally initiate full power braking as soon as they see an obstacle—if only to avoid being hit from behind. On the other hand, if they brake too lightly at first, they will run out of braking power so that they are in a "crash state" well before the actual collision. How do drivers use visual cues to adjust their braking? Lee suggests that this could be done on the basis of rate of change of time to collision. Suppose that at time t the driver is at distance d from the obstacle, the vehicle's instantaneous velocity is v, and the driver is braking with deceleration a. Clearly, the deceleration is adequate if the distance that it will take the vehicle to stop is less than distance d, that is,

$$\frac{v^2}{2a} < d .$$

Therefore

$$\frac{da}{v^2} > 0.5 . \tag{5}$$

Now the instantaneous time to collision is given by

$$T = \frac{d}{v} . \tag{6}$$

Differentiating Eq. (6) with respect to time,

$$\frac{da}{v^2} = 1 + \frac{dT}{dt} . \tag{7}$$

Hence from Eqs. (5) and (7) the driver's braking is adequate if $dT/dt > -0.5$. In words, the driver's braking is adequate if the rate of change of time to collision is greater than -0.5.

A second problem discussed by Lee (1980) is how long jumpers adjust their stride length as they approach the takeoff board. Movie films showed that jumpers do not use a standard run-up. Instead, they adjust their stride length during the approach. Lee suggested that the relevant cue was time to reach the board, and that the task of zeroing in on the board can be conceived of as programming the durations of the forthcoming strides to just fill the time remaining to reach the board. Thus Lee proposed a temporal conception of this visual-motor coordination task rather than a spatial conception such as, for example, programming stride lengths.

Schiff and Detwiler (1979) studied the information used in judging impending collision. They had 36 subjects view motion pictures of plain black disks that appeared to move toward them along a simulated "terrain" separated from a "sky" by a horizontal line. In some conditions a rectangular grid added texture to the terrain, the sky, or both. The simulated approaching velocities and distances of motion are summarized in Table 19.1.

The experimenters found that judgments of time to collision increased monotonically with the actual time to collision, as shown in Figure 19.12. However, there was a consistent tendency to underestimate time to collision as its actual value increased. In addition, variance in the judgment of time to collision also increased, nearly in proportion to the actual time to collision. As illustrated in Figure 19.12(b), there was a similar relationship between object velocity and judged time to collision.

The study suggested that the primary information used by the subject was the changing size of the target. The stimuli were all motion pictures, so no stereoscopic three-dimensional information was available. Also, there were no significant differences in performance that could be attributed to the presence or absence of texture (the grids). Finally, the judgments were essentially invariant over several object sizes, object velocities, and viewing distances. One major limitation in this experiment is that the moving target was never permitted to get closer than a simulated distance of about 300 m. Because in normal

Table 19.1. Stimulus Conditions for the Experiment in Judging Time to Collision, T_C (see Figure 19.12)

	Simulated Distance (*m*)		Velocity	
T_C	Start	Final	$km \cdot hr^{-1}$	$cm \cdot sec^{-1}$
10	660	300	18	11
10	720	600	36	22
8	375	300	22.5	14
8	750	600	45	28
6	399	300	30	19
6	798	600	60	38
4	450	300	45	28
4	900	600	90	56
2	600	300	90	56

Subjects viewed films of a black disk approaching along one of several stylized backgrounds. In one condition, only a "horizon" line was present to differentiate sky and terrain; in other conditions, the "terrain," the "sky," or both were covered by a grid pattern. Stimuli were produced by filming black forms using animated tabletop photography. The camera was aimed slightly downward to approximate the direction of gaze of an erect pedestrian watching an approaching automobile. Actual distances and velocities were rescaled to provide the corresponding real-world equivalents shown in the table on the assumption that the 3-cm disk corresponded to an object that was actually 150 cm in diameter (the approximate width of an automobile). (From W. Schiff & M. L. Detwiler, Information used in judging impending collisions, *Perception*, 1979, *8*. Reprinted with permission.)

life estimates of time to collision can be highly accurate when the distance is short—as, for example, in avoiding a cricket ball (Regan, Beverley, & Cynader, 1979), these data have limited applicability. Even so, the predominant role of changing size and the weak effect of background texture are highly significant. A similar failure of background texture to aid performance was found in judgments of the impact point on the surface of an aircraft carrier during a simulated landing (Kaufman, 1964).

2.2.2.5. Looming and Texture Changes. The studies by Schiff and Detwiler (1979) and Kaufman (1964) cited above suggest that background texture has little effect on the perception of changing size and motion in depth. The situation is quite different, however, with regard to object texture, which exerts a strong effect on the perception of motion in depth. In a study of visual responses to changes in depth, Regan and Beverley (1983b) attempted to compare the contributions of texture and looming by pitting one against the other. Figure 19.13 illustrates some of the electronically generated stimuli they used.

As described in Section 2.2.3.2, after inspection of an adapting square whose size increases, a subsequently viewed test square of constant size appears to be moving away in depth, provided that the adapting and test squares are about the same size. This motion-in-depth aftereffect was used to quantify the effectiveness of the displays in Figure 19.13 as stimuli for motion in depth. This indirect procedure was used because (1) the motion-in-depth aftereffect is supposed to be due to a specific motion-in-depth mechanism in the visual pathway (Regan & Beverley, 1978a); (2) the aftereffect was usually an unequivocal sensation of motion in depth, unaccompanied by any confounding sensations such as size change or texture change.

In this experiment, texture change either assisted looming or opposed it. A motion-in-depth aftereffect was produced by inspecting a textured square that contracted in overall size at $24\% \cdot sec^{-1}$. The magnification of the texture of the adapting square increased or decreased at different rates. The motion-in-depth aftereffect was roughly constant when texture contracted as for a real-world solid object ($24\% \cdot sec^{-1}$) or faster. However, when texture was static or opposed looming, the motion-in-depth aftereffect was virtually destroyed (see Figure 19.14). A similar but reversed effect was observed for an expanding square.

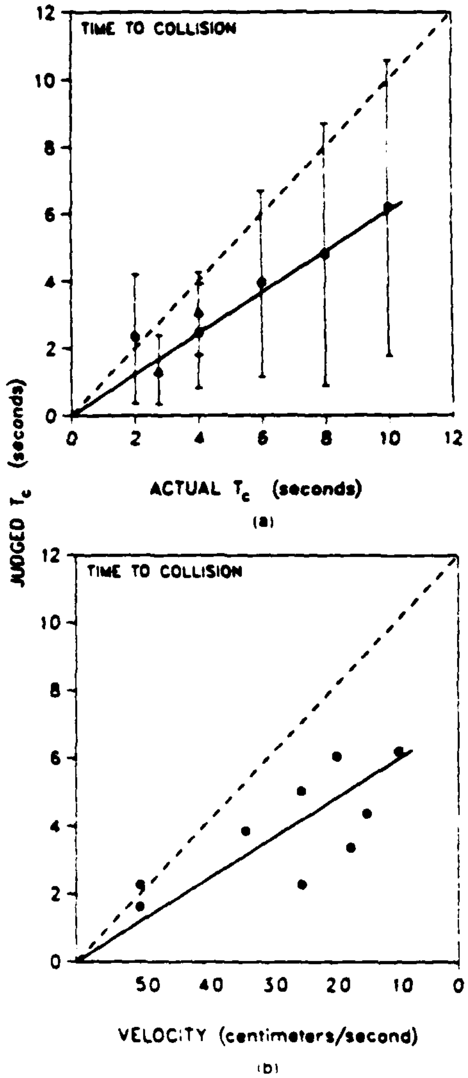


Figure 19.12. Judged time to collision (T_c) as a function of actual time to collision and stimulus velocity. Subjects viewed a film sequence in which a black disk approached at various speeds along a stylized terrain and estimated the time at which the disk would reach them. (See Table 19.1 for a listing of the stimulus conditions.) Panel (a) shows an approximately linear relationship between estimated time to collision (ordinate) and actual time to collision (abscissa) with the disk (round symbols). Data points for 4–10 sec are averages of 144 responses by each of 36 subjects, the data point for 2 sec is based on 36 judgments by 18 subjects. Triangles are averages of 36 similar time-to-collision judgments by each of 36 subjects in response to films of automobiles approaching head-on at about $64 \ km \cdot hr^{-1}$. There is an approximately proportional increase in variability of judgments with time to collision (vertical bars show standard deviations). The slope of the function is < 1.0, indicating a tendency to underestimate time to collision. Panel (b) shows that judged time to collision was also underestimated relative to actual object velocity, especially for real velocities less than about $40 \ cm \cdot sec^{-1}$. (From W. Schiff & M. L. Detwiler, Information used in judging impending collisions, *Perception*, 1979, *8*. Reprinted with permission.)

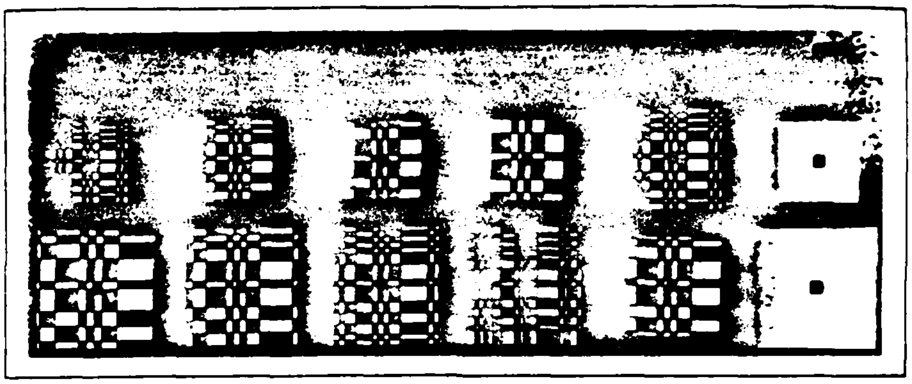


Figure 19.13. Independent manipulation of size and texture grain. A–F show some of the different adapting stimuli used to compare the effectiveness of size and texture changes in producing the sensation of motion in depth. Stimulus B corresponds to a solid real-world object whose magnification is changing. In A texture elements contract faster than square size and in C texture grain is constant. Changes in texture and size are antagonistic in D. In E size is constant whereas texture contracts. F is an untextured square. Mean square side length was 1.2°, square size contracted or expanded at 17 min arc·sec^{-1}, and presentation duration was 1.7 sec. These are photographs of the CRT displays used. (From K. I. Beverley & D. Regan, Texture changes versus size changes as stimuli for motion in depth, *Vision Research*, 1983, *23*. Reprinted with permission.)

Even with the fastest rates of texture change, an untextured square was usually a better motion-in-depth stimulus than a textured square. These findings suggest that, although texture may well be important in representing such static features as curvature, in terms of the monocular simulation of motion in depth the presence of object texture adds little at best, and if texture dynamics and looming dynamics are not accurately matched, texture detracts from motion in depth. This experiment draws attention to the importance of dynamic features of visual flight simulation, in contrast to the emphasis on static picture quality that has traditionally been the chief criterion of quality in simulator displays.

2.2.3. Stereopsis and Changing Size. Stereoscopic depth perception has been a research topic since Wheatstone (1838) demonstrated that binocular disparity alone produces a compelling impression of solidity and depth. In recent years the topic has been given a fresh impetus by Julesz's (1971) development of random dot and dynamic random dot stimuli. The classical stereoscopic system in the human visual pathway mediates the perception of position in depth, and in particular the perception of depth relative to the point of ocular convergence. This section discusses the hypothesis that there is a second stereoscopic system that is substantially independent of the classical stereoscopic depth system. This second system is sensitive to the direction of motion in depth. It operates in parallel with the classical system rather than sequentially, and is not merely derived from the rate of change of disparity. The stimulus for this second system is the ratio of the retinal image velocities in the left and right eyes. There is evidence that different neurons mediate the classical depth system and the motion-in-depth system.

A compelling sensation of motion in depth can be produced either by stereoscopic stimulation or by looming stimulation. The following section also discusses the relative effectiveness of these two stimuli in generating a sensation of motion in depth.

2.2.3.1. Two Stereoscopic Systems: One for Motion, One for Position. Beverley and Regan (1973a, 1973b) pointed out that the relative velocities of the left and right retinal images provide a precise stereoscopic cue to the direction of motion in depth (Figure 19.15). In psychophysical experiments they found that the threshold for detection of motion in depth along a straight line was elevated after inspection of a stimulus that oscillated in depth. This effect occurred only over a limited range of directions of motion in depth. As shown in Figure 19.16, inspection of an object that moved along a line inclined to the left of the nose elevated the threshold for stereoscopic motion in depth for all test trajectories inclined to the left of the nose, but had little effect for test trajectories inclined to the right of the nose. Similarly, inspecting an object oscillating in depth along a line inclined to the right of the nose elevated threshold for stereoscopic motion in depth for all test directions inclined to the right of the nose, but had little effect for test trajectories inclined to the left of the nose. Beverley and Regan proposed that the data shown in Figure 19.16 demonstrate a specific visual sensitivity to the direction of motion in depth. They postulated four pairs of stereoscopic motion-in-depth channels, tuned to different ratios of left/right image velocity and hence to four different directions of motion in depth. Figure 19.17(b) shows the directional tuning of these channels as derived from the data of Figure 19.16.

The dynamic properties of the system mediating perception of motion in depth are quite different from the dynamic properties of vision for frontal plane motion. In one experiment (Regan & Beverley, 1973) subjects viewed a bar or dot pattern that oscillated from side to side at a slightly different frequency in each eye. The target appeared to change its position in depth at the difference frequency of the oscillations in each eye, although neither eye alone had access to this frequency. With this technique, it is possible to measure monocular sensitivity to motion in the frontal plane while simultaneously measuring stereoscopic sensitivity to motion in depth. Visual sensitivity to frontal plane oscillations was found to reach a maximum at 1–4 Hz. Such motion was visible at frequencies as high as 25 Hz. In contrast, sensitivity to stereoscopic motion in depth was greatest at the lowest frequency measured (difference frequency of 0.75 Hz). Stereoscopic visual sensitivity breaks down so that

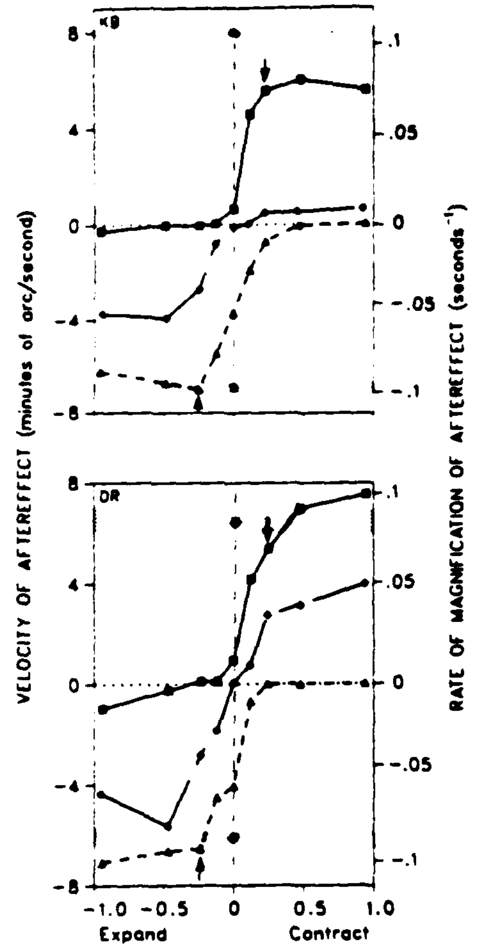


Figure 19.14. Size and texture compared as stimuli for motion in depth. Subjects viewed textured squares similar to those in Figure 19.13 that changed in overall size and in magnification of texture elements. After 10 min of adaptation to one of these stimuli, subjects viewed an untextured test square that changed in size and adjusted the rate of size change just to cancel the motion-in-depth aftereffect produced by the adapting stimulus. Ordinates plot the strength of motion-in-depth aftereffects caused by adapting to textured squares that contracted at a fixed rate (upper curves, squares), expanded at the same fixed rate (lower curves, triangles), or remained constant in size (middle curves, diamonds). Magnification of the texture elements of the adapting square decreased or increased independently of the square's overall size change at the rates shown on the abscissas. Arrows mark the points at which rate of change in the magnification of texture elements matched rate of change in overall size of the stimulus square (24% $\cdot$ sec^{-1}). The asterisks at zero on the abscissas plot the aftereffect caused by an untextured adapting square. The vertical extent of the shaded areas shows ± 1 SE. Otherwise, SEs were smaller than the symbols. Data are shown for two subjects. For rates of texture magnification equal to or greater than the rate of overall size change, the motion-in-depth aftereffect remained relatively constant; however, the aftereffect was virtually absent when texture was static or texture element magnification was in a direction opposite to overall size change. (From K. I. Beverley & D. Regan. Texture changes versus size changes as stimuli for motion in depth. *Vision Research*, 1983, *23*. Reprinted with permission.)

no oscillation in depth can be seen at all at frequencies higher than about 4–5 Hz. These data are illustrated in Figure 19.18.

This sluggishness of the stereoscopic system may be connected with the slow convergence response to an abruptly introduced disparity (Rashbass & Westheimer, 1961; Westheimer & Mitchell, 1956). The reaction time for convergence is about 160 msec, and convergence to a new position may take as long as 800 msec—a substantial time as compared with conjugate saccadic or pursuit eye movements.

The ability to discriminate between different directions of stereoscopic motion in depth is remarkably acute. A difference of as little as 0.1–0.2° in direction may be detectable (Beverley & Regan, 1975).

Figure 19.17(a) summarizes about 10,000 observations in which subjects had to discriminate between different directions of motion in depth. The retinal velocity ratios of the images in the two eyes (V_L/V_R) were adjusted to simulate objects that hit or just missed the head as they approached the observer.

The high acuity of 0.1–0.2° shown in Figure 19.17(a) cannot be entirely explained by assuming that the most active of the four directionally selective channels of Figure 19.17(b) signals direction. This model would predict an acuity of only about 1–2°. To account for this higher acuity, Beverley and Regan (1975) proposed that discrimination among different directions of motion in depth is determined by the relative outputs of the four channels of Figure 19.17(b), a proposal similar to the ideas that our acute wavelength discrimination is determined by the balance of activity of three rather broadly tuned color mechanisms, that spatial frequency discrimination is determined by the relative activities of spatial frequency channels (Campbell, Nachmias, & Jukes, 1970; Regan & Beverley, 1983b) and that orientation discrimination is determined by the relative activity of orientation-tuned mechanisms (Regan, 1982; Regan & Beverley, 1984c; Westheimer, Shimamura, & McKee, 1976).

2.2.3.2. Aftereffects of Motion in Depth and of Changing Size. Prolonged inspection of an object whose size is changing causes a subsequently viewed object of constant size to appear to be either changing in size or changing in depth. Regan and Beverley (1978a) had subjects view a bright square that increased in size for 1.0 sec. After steadily fixating the square over repeated expansion cycles, subjects looked at a static test square which then appeared to be moving away in depth. An aftereffect was also observed when the adapting square shrank horizontally but remained constant in size vertically (Beverley & Regan, 1979). At first the test square did not appear to move forward in depth, but it did appear to expand in width. However, this initial aftereffect was replaced (often abruptly) by a motion-in-depth aftereffect in which the square appeared to be moving forward rather than expanding.

These aftereffects were measured by having subjects adjust rate of size change in a test square that shrank horizontally so as to null either its apparent motion in depth or its apparent changing size. Figure 19.19 shows that both aftereffects decay exponentially, but the aftereffect of changing size has a much shorter time constant than does the aftereffect of motion in depth. For four subjects, the mean time constants for changing size ranged from 7.9 to 9.9 sec, whereas the time constants for motion in depth ranged from 21 to 47 sec. It may be significant that the decay time constant for the elevation of stereoscopic motion-in-depth threshold following exposure to changing binocular disparity (Beverley & Regan, 1973a) is roughly equivalent to the 21–47 sec decay time constants for motion in depth aftereffects due to a stimulus that is changing in size, as described above.

Regan and Beverley (1978b) tested the hypothesis that the motion-in-depth aftereffect is truly an aftereffect of velocity. When only one test ramp duration is used (where the slope of the test ramp represents the rate of size change), the rate of expansion of the test square whose changing size is being ad-

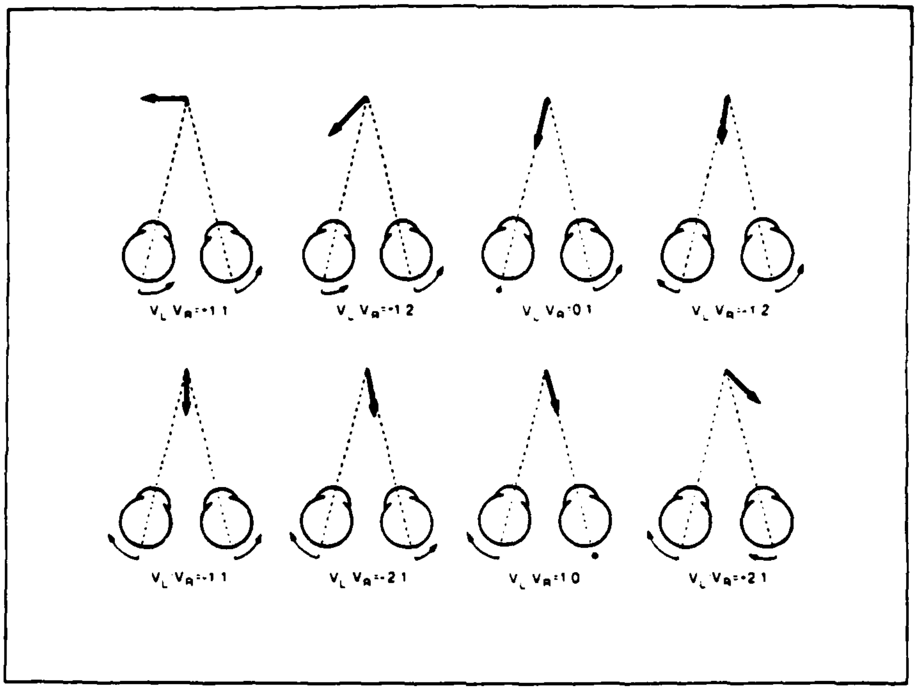


Figure 19.15. Relative velocities of left and right retinal images for different target trajectories. When the target moves along a line passing between the eyes, its retinal images move in opposite directions in the two eyes: when the target moves along a line passing wide of the head, the retinal images move in the same direction, but with different speeds. The ratio (V_L/V_R) of left- and right-eye image velocities provides an unequivocal indication of the direction of motion in depth. (Modified from Beverley & Regan, 1973a.)

justed by the subject is confounded with the absolute increase in size of the test square. To unconfound these two parameters, the experiment described above was repeated using two different test ramp durations—3.3 and 1.0 sec. When canceling velocity is plotted against time, the data points superimpose for both test durations. However, when the amplitude of the canceling stimulus (final side length minus initial side length) is plotted against time, the data points for the two durations do not coincide. This finding indicates that the effective feature of the canceling stimulus is the rate of change of size.

The growth of the motion-in-depth aftereffect follows a function that differs from the one describing its decay. Buildup continues for at least 10 min and is not exponential. The canceling rate of change of size is proportional to the square root of the time of exposure, so growth follows a power law. For decay, the canceling rate of change in size falls exponentially, and at time t in seconds is

$$V_t = K \exp\left(\frac{-t}{\tau}\right)$$

where τ is the time constant and V_t is the canceling rate of change of size (Regan & Beverley, 1978b).

2.2.4. *Kinetic Aftereffects and Motion in Depth.* As we have seen, an increase in an object's retinal image size can mean either that it is expanding or that it is moving in depth. As described previously, other kinds of transformations in the picture plane also produce impressions of motion in depth. The kinetic depth effect (KDE) of Wallach and O'Connell (1953) is one example. In their view, the perception of a rigid object rotating in depth depends on change in both the lengths and directions of its contours over time. Objects with contours that do not change along one of these dimensions are ambiguous stimuli in that they may be seen as moving in depth at some times, or undergoing rubbery transformations at other times. Fieandt and Gibson (1959) also noted that rigid objects seen from a succession of different vantage points constitute one kind of stimulus to vision, whereas "rubbery transformations" constitute another. Beverley and Regan (1979) suggested that a "safest guess" strategy may operate in that the visual system is biased to signal that a looming predator is approaching rather than the predator is growing in size. Their suggestion was based on the finding that a changing-size aftereffect is *not* produced by adaptation to a target whose size changes uniformly as though viewed through a zoom lens: a motion-in-depth aftereffect alone is seen. Only when the object's shape is distorted while its size changes is a changing-size aftereffect produced, suggesting that the visual system is biased toward motion-in-depth rather than changing-size responses.

Ullman (1979) made a similar suggestion and in one experiment created a stimulus composed of dots distributed at random on the surfaces of two concentric and transparent cylinders. The cylinders were invisible and the dots were projected onto a screen where they looked like a flat array of random dots. When the cylinders were made to rotate stroboscopically in opposite directions, the subject saw two rigid cylinders rotating in depth about their vertical axes. This perception was but one of several alternatives. Because the dots were moving stroboscopically, they might just as well have been perceived as executing a random snowlike motion. However, the resulting KDE was clearly the preferred alternative for the perceptual system.

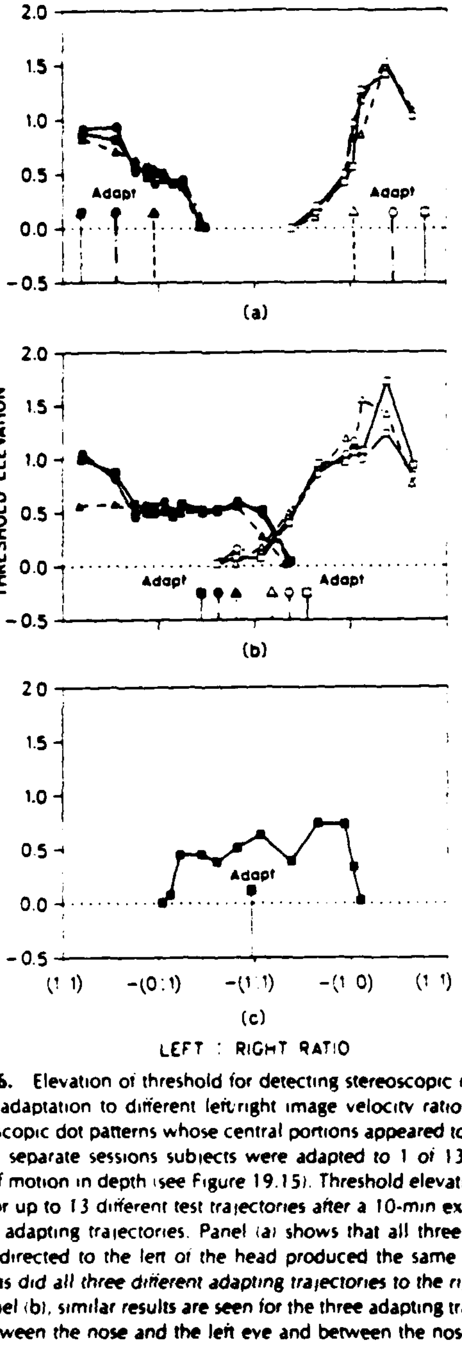


Figure 19.16. Elevation of threshold for detecting stereoscopic motion in depth after adaptation to different left/right image velocity ratios. Stimuli were stereoscopic dot patterns whose central portions appeared to oscillate in depth. In separate sessions subjects were adapted to 1 of 13 different directions of motion in depth (see Figure 19.15). Threshold elevations were measured for up to 13 different test trajectories after a 10-min exposure to each of the adapting trajectories. Panel (a) shows that all three adapting trajectories directed to the left of the head produced the same threshold elevations, as did *all three different adapting trajectories to the right of the head*. In panel (b), similar results are seen for the three adapting trajectories directed between the nose and the left eye and between the nose and the right eye. As shown in panel (c), motion directly toward the nose produced symmetrical elevations. The pattern of threshold elevations produced by the 13 different trajectories can be parsimoniously explained in terms of four mechanisms tuned to different values of V_L/V_R, as shown in Figure 19.17(b). (From K. I. Beverley & D. Regan, Evidence for the existence of neural mechanisms selectively sensitive to the direction of movement in space. *Journal of Physiology*, 1973, 235. Reprinted with permission.)

As noted earlier, inspecting a rectangle that changes in size in one dimension only produces first an aftereffect in which a static test rectangle appears to change size (and thus shape) without moving in depth; then this aftereffect abruptly changes into one in which the test rectangle appears to move in depth without changing size. This suggests that the perceptions of changing size and of motion in depth are mediated by at least partially different neural mechanisms, and that there is some antagonism between these two mechanisms (Beverley & Regan, 1979).

2.2.4.1. Interaction of Kinetic Aftereffects with Disparity. **Although partially independent mechanisms may mediate alternative modes of perception, there is strong evidence that kinetic cues to depth affect the depth perception related to static binocular disparity. Wallach and Karsh (1963) had subjects**

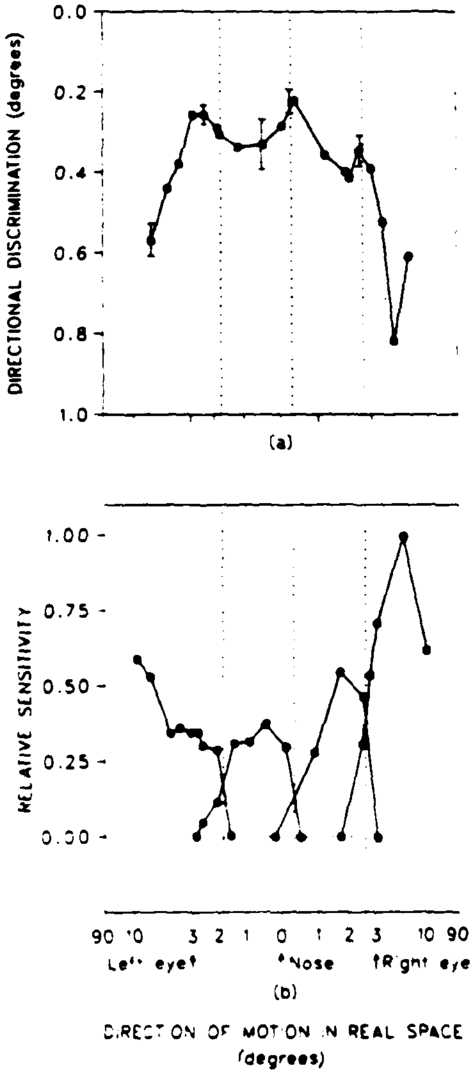


Figure 19.17. Stereoscopic discrimination of the direction of motion in depth. Panel (a) shows how angular discrimination of direction (ordinate) is related to the actual direction of a target's trajectory (abscissa). This figure, based on about 10,000 observations, demonstrates a very accurate discrimination of roughly 0.2° among trajectories hitting or just missing the head. *Standard deviations are represented by the vertical bars. Panel (b) is derived from the data of Figure 19.16. The results of Figure 19.16 can be explained in terms of four pairs of channels tuned to different values of V_L : V_R (left/right image velocity ratios). These hypothetical channels underlie the operation of a stereoscopic subsystem that responds to motion in depth, as opposed to the classic stereoscopic subsystem that responds to static disparity (relative static position in depth).* (From K. I. Beverley & D. Regan, The relation between discrimination and sensitivity in the perception of motion in depth. *Journal of Physiology*, 1975, 249. Reprinted with permission.)

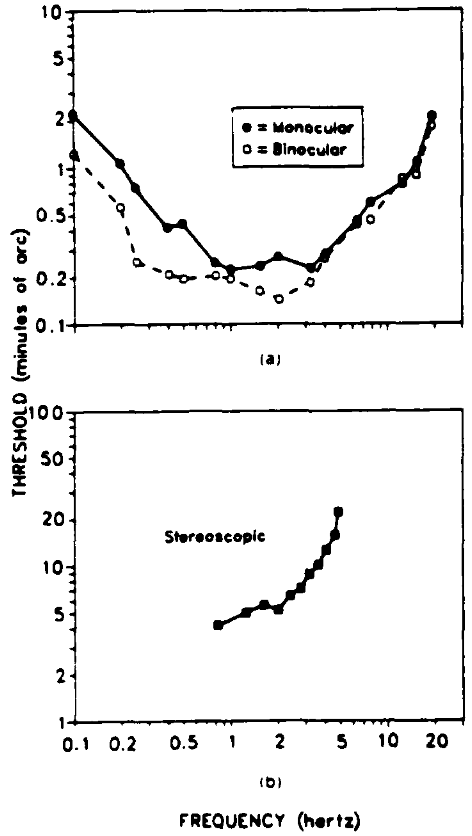


Figure 19.18. Comparison of visual sensitivity to positional oscillations in the frontal plane and to stereoscopic oscillations in depth. The subject's left eye viewed a bar or dot pattern that oscillated from side to side at a frequency F Hz while the right eye viewed a similar pattern oscillating at $(F + \Delta F)$ Hz. At the difference frequency of ΔF, oscillations in depth waxed and waned, but monocular signals were at either F or $(F + \Delta F)$ and had no component at frequency ΔF. Thus the technique provides a subjective distinction between stereoscopic and monocular processing by giving them quite different frequency "signatures." Panel (a): sensitivity to oscillation in the frontal plane is maximal at 1–4 Hz, with somewhat greater sensitivity at low frequencies under binocular viewing conditons with ΔF at zero (dashed curve). Frontal plane oscillations are still visible at 25 Hz, although sensitivity is much reduced. Panel (b): sensitivity for stereoscopic oscillation in depth falls off with increasing frequency from the lowest frequency measured (0.75 Hz). Oscillation in depth could not be seen at or above 3 Hz for one subject, and 5 Hz for another. (From D. Regan & K. I. Beverley, The dissociation of sideways movements from movements in depth: Psychophysics, *Vision Research*, 1973, *13*. Reprinted with permission.)

view a slanted wire pyramid through a telestereoscope that increased the disparity of its half images (see Figure 19.20). The enhanced disparity caused subjects to judge the distance between the nearer apex of the pyramid and its more distant base as being much greater than when the pyramid was seen without the telestereoscope. Then the pyramid was rotated so that each eye obtained the same kinetic information as to depth (the KDE was the same for both eyes), except that it was in opposite phases in the two eyes. At first the pyramid exhibited a rubbery distortion, but after a while it was perceived as rigid and rotating in depth.

After viewing the rotating pyramid through the telestereoscope for several minutes, subjects judged the depth between the apex and base of the static pyramid once again while looking at it directly. It was found that the amount of depth given by the static disparity was substantially altered as a result of adaptation to the kinetic cues. This rapid modification of the stereoscopic depth effect suggests that the amount of depth associated with different disparities can be rescaled by exposure to (monocular) kinetic cues.

Wallach and Frey (1972) placed changing size in conflict with the cues of accommodation, convergence, and disparity. This was done by moving a luminous diamond-shaped object toward and away from an observer, but expanding and diminishing its size as it moved. The actual path length was 55 cm, with the nearer point 25 cm from the subject and the farther point 80 cm away. Although the path was only 55 cm long, the size of the diamond was varied while it moved to simulate a path length of 367 cm. Thus the change in image size was greater than the changes induced in absolute disparity and accommodation.

As pointed out in Chapter 23 by Arditi, the amount of depth perceived between two objects is a function of both the distance to the objects and the relative binocular disparity. For a constant relative disparity, the amount of perceived depth between two objects increases as the square of the average distance to them. Hence a change in perceived distance should result in a marked change in perceived depth based on relative disparity. If the changing size utilized by Wallach and Frey resulted in an increase in perceived distance, then a stereoscopic depth effect should be enhanced.

It is also well known that the perceived frontal size of an object of constant linear size is proportional to its perceived distance (Emmert's law). Hence an increase in perceived distance due to exposure to the changing-size stimulus should also result in an increase in judged frontal size.

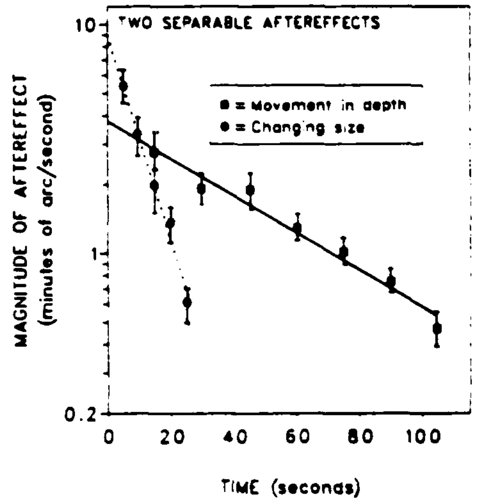


Figure 19.19. Decay curves for motion-in-depth and changing-size aftereffects. The adapting stimulus was a bright solid square of mean size 1° on a side. During adaptation, the vertical edges moved toward each other at a rate of $0.25° \cdot sec^{-1}$ for 1 sec; horizontal edges remained stationary. The square then disappeared for 0.25 sec and the cycle was repeated. After 20 min of exposure to the adapting stimulus, a static test square appeared either to expand in size or to move forward in depth. In one experiment, subjects canceled the changing-size aftereffect by adjusting the rate of size change in a 1° test square whose vertical edges moved toward each other (dotted line). In another experiment, subjects canceled apparent movement in depth in the same manner (continuous line). (Modified from Beverley & Regan, 1979.)

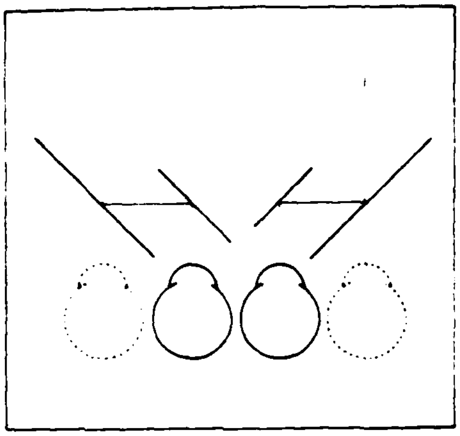


Figure 19.20. The principle of the telestereoscope. The images of the world reflected by the mirrors to the two eyes are "seen" from station points that are set farther apart than the eyes themselves. This has the effect of enlarging the interpupillary distance. It also enhances the magnitude of depth between points at different distances, because the disparity of these points is increased. (From L. Kaufman, *Sight and mind*, Oxford University Press, 1974. Reprinted with permission.)

To test for these effects Wallach and Frey had observers estimate the size of the base of a luminous wire pyramid facing them, and also the depth between the base and the more distant apex of the pyramid. This was done for pyramids at two different distances both before and after adaptation to the changing-size diamond. The estimates of size and depth were made by having subjects adjust the length of a rod held in their hands but not seen. In general, the rod was made longer after adaptation than before. The base of the near pyramid was judged to be about 10% larger after adaptation than before; the base of the more distant pyramid, about 16% larger. The judgments of depth were even more markedly affected. Although the disparity of both the near and more distant pyramids was the same before and after adaptation, the perceived depth increased by 19% for the near pyramid and 28% for the far pyramid. This finding indicates that the distance information given by absolute disparity and accommodation was altered by observation of nonveridical changing size.

2.2.4.2. Comparison of Changing Size and Changing Disparity as Stimuli for Motion in Depth Perception. As shown in Figure 19.21, when an object moves directly toward the head, the two retinal images move away from each other (their disparity increases), and the images also grow larger. As discussed above, either of these two consequences of object motion is capable of producing a sensation of motion in depth. In the real visual world the situation is almost always as shown in Figure 19.21, but Regan and Beverley (1979a) placed changing size and changing disparity in opposition to each other in order to measure their relative efficacy as stimuli for motion in depth. In their experiment, when decreasing disparity indicated that a square was coming closer, the sizes of its retinal images grew smaller rather than larger.

The task of the subject was to null the motion in depth of a square produced by changing size by adjusting the rate of change in the disparity of its two retinal images. Figure 19.22 shows the relationship between the rate of change in disparity and the rate of change in size that was nulled by this rate of change in disparity. The fact that nulling is possible at all indicates that the perception of motion in depth is the same thing, whether produced by looming stimulation or by changing disparity stimulation; presumably, signals generated by these two stimuli converge before reaching the neural mechanism whose activity corresponds to the sensation of motion in depth. The plots are roughly linear on log-log axes, indicating a power function relationship. The relative effectiveness of the two stimuli is also affected by the duration of the inspection period. Furthermore, in a sample of five subjects, an 80:1 intersubject difference was seen in the relative effectiveness of changing size and changing disparity as stimuli for perception of motion in depth.

Now we turn to the question of what effect viewing distance has on the relative effectiveness of changing disparity and changing size as stimuli for motion in depth perception. It can be shown that, on geometric grounds, viewing distance has no effect on the ratio between change in stimulus size and change in stimulus disparity.

As shown in Figure 19.23, when an object of linear width S moves from a viewing distance D to distance $(D - \Delta D)$, the size of its retinal images increases from θ_S to θ_S' radians, and the binocular disparity changes from θ_D to θ_D' radians. Approximately, $\theta_D = I/D$, $\theta_D' = I/(D - \Delta D)$, $\theta_S = S/D$ and $\theta_S' = S/(D - \Delta D)$. Hence $(\theta_D' - \theta_D) = \Delta\theta_D = (I\Delta D)/D^2$ and $(\theta_S' - \theta_S) = \Delta\theta_S = (S\Delta D)/D^2$. Thus $\Delta\theta_S/\Delta\theta_D = S/I$. Hence $\dot{\theta}_S/\dot{\theta}_D = S/I$. This means that the ratio between the rate of change in binocular disparity ($\dot{\theta}_D$) and the rate of change in size ($\dot{\theta}_S$) does not depend on viewing distance, but does depend on the absolute width of the object and on the observer's interpupillary distance. A more detailed proof is given in the Appendix. The independence of viewing distance may seem counterintuitive since classical binocular depth perception is almost ineffective at ranges greater than about 100 m. However, it is the ratio $\dot{\theta}_D/\dot{\theta}_S$ that is important here, whereas classical depth perception depends on absolute disparity rather than a ratio.

The effect of viewing distance is not necessarily only a geometrical issue, however, for binocular convergence is different for different viewing distances, and the angle of convergence

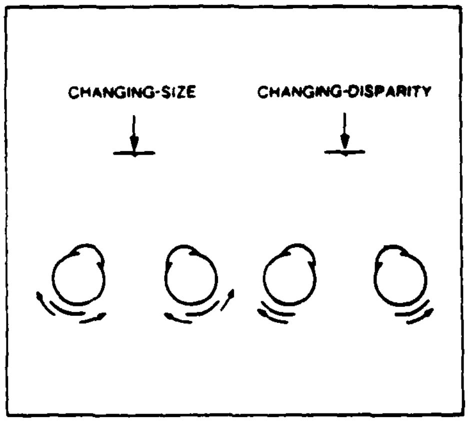


Figure 19.21. Effect on retinal images of changing size and changing disparity. When a solid and nonrotating object moves toward the head, its half-images change in size, as shown on the left. Also, the left and right half-images move away from each other (change in absolute disparity), as shown on the right. Both kinds of change, that of image size and that of absolute disparity, occur simultaneously when an object moves toward the head in real space. (From D. Regan & K. I. Beverley. Binocular and monocular stimuli for motion-in-depth: Changing-disparity and changing-size inputs feed the same motion-in-depth stage, *Vision Research*, 1979, *19*. Reprinted with permission.)

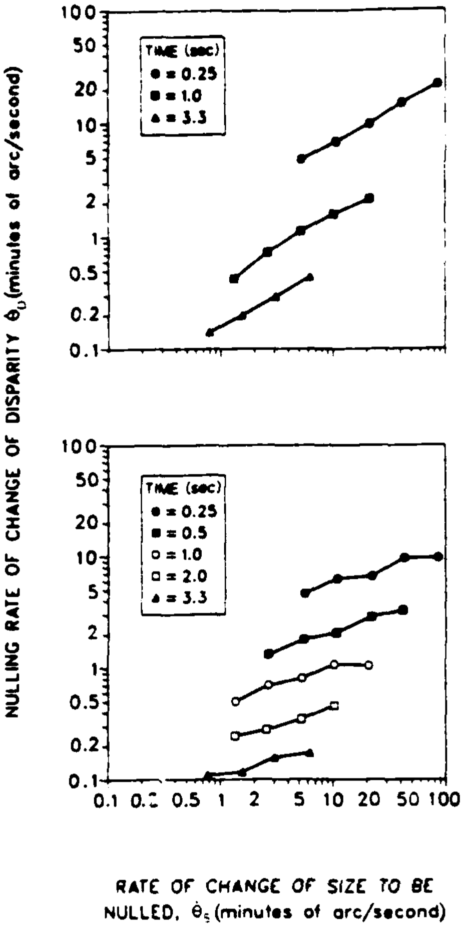


Figure 19.22. Relative effectiveness of binocular and monocular cues for motion in depth. Subjects viewed a square of mean size 1° that expanded at a uniform speed for 0.25, 1.0, or 3.3 sec. The disparity of the square could be altered simultaneously by the subject so as to cancel the impression of motion in depth produced by the changing size. Repeated observations were made at each inspection time until a satisfactory null was achieved. Ordinates plot the rate of change of binocular disparity required to cancel the sensation of motion in depth produced by different rates of size change (abscissas). Data are shown for two subjects. The relative effectiveness of changing size and changing disparity as stimuli for motion in depth depends on rate of size change and inspection time. (From D. Regan & K. I. Beverley, Binocular and monocular stimuli for motion-in-depth. Changing-disparity and changing-size inputs feed the same motion-in-depth stage, *Vision Research*, 1979, *19*. Reprinted with permission.)

is known to affect perceived size. Control experiments in which the angle of convergence was varied by means of prisms upheld the conclusion that viewing distance does not substantially alter the relative effectiveness of changing size and changing disparity as cues to motion in depth (Regan & Beverley, 1979a).

It is clear from Figure 19.21 that changing-size stimulation is available either binocularly or monocularly. However, changing disparity is only available binocularly. A question that has attracted considerable interest is whether the absence of binocular vision affects pilot performance. Three flight studies revealed that landing performance of pilots in daylight was not degraded by the occlusion of one eye (Grosslight, Fletcher, Masterton, & Hagen, 1978; Lewis, Blakeley, Swaroop, Masters, & McMurty, 1973; Pfaffman, 1948), and one study reported that landing performance could even be improved by loss of binocular vision (Lewis & Kriers, 1969). This latter finding was challenged by other researchers who, nevertheless, found that monocular performance was no worse than binocular performance (Grosslight et al., 1978). The suspicion that pilots might try harder when one eye is occluded was addressed by performing an experiment with relatively inexperienced ("low-time") pilots rather than experienced military pilots. Even though the low-time pilots were presumably stressed when landing normally with full binocular vision, monocular occlusion produced no reduction in landing performance (Lewis & Kriers, 1969).

The results of these flight tests are consistent with the notion that, when other depth cues are available, static binocular depth perception is unimportant at ranges in excess of about 90 m. (Of course, there may well be other advantages to binocular vision in piloting aircraft because, for example, it provides a wider field of view than does vision with one eye occluded.)

There is evidence, however, that stereoscopic sensitivity to motion in depth is a different matter from classical stereoscopic sensitivity to position in depth. As discussed above, the ratio between sensitivity to binocular motion cue and to the looming cues is little affected by viewing distance over a large range of distances. Laboratory experiments (Regan & Beverley, 1979a) suggest that the flight tests discussed above may have confounded several factors, so that their results may be applicable to only a narrow range of visual situations. To make this clear, consider the consequences of loss of binocular vision for sensitivity to motion in depth of objects on the ground during landing. This sensitivity would depend on the following four factors (Regan & Beverley, 1979a):

1. *Inspection Duration.* A loss of binocular vision would be less important for short periods of inspection.
2. *The Target's Velocity in Depth.* Visual sensitivity to low velocities would be less affected by losing binocular vision.
3. *The Absolute Width of the Object.* Visual sensitivity to motion in depth of wider objects would be less affected by loss of binocular vision than would sensitivity to motion in depth of narrower objects (except at very short distances; see Regan and Beverley, 1979a).
4. *Individual Differences.* There are very large individual differences in relative sensitivity to changing size and to changing disparity; for example, as noted earlier, individuals differ in sensitivity to changing disparity by as much as 80 to 1.

Calculations have been published (Regan & Beverley, 1979a) to illustrate how the relative effectiveness of monocular and binocular stimuli to motion in depth can be computed for individual observers in real visual situations, including aircraft landings.

The following calculation illustrates how targets of narrow width (in centimeters rather than angular subtense) favor the stereoscopic (binocular) stimulus for motion in depth over the changing size stimulus. Suppose that an object 15.24 cm in diameter is 90 m from an aircraft and approaching it at a closing line-of-sight velocity of 260 km·hr^{-1}. From geometric considerations the ratio of the rate of change in disparity to the rate of change in angular size is equal to I/S, where I is the interpupillary distance and S the angular size of the object. At 90 m the object's angular size is about 10 min of arc and its rate of change in size is about 3.6 min arc·sec^{-1}. Now consider the psychophysical data for one subject shown in Figure 19.22 (lower panel). If the inspection time is 1.0 sec, then, before

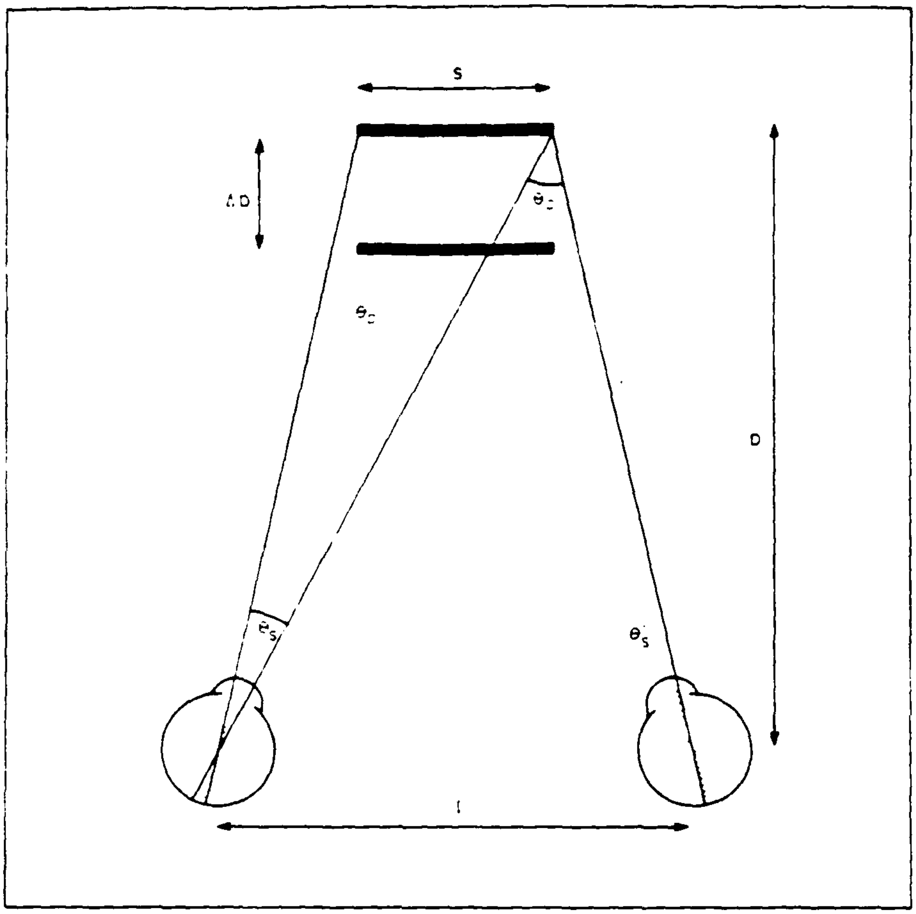


Figure 19.23. Geometric relation between rate of change of size and rate of change of disparity. When an object of linear width S moves from viewing distance D to distance $(D - \Delta D)$, retinal image size increases from θ_S to θ_S' rad, and binocular disparity changes from θ_D to θ_D'. See text for proof that the ratio between the rate of change of binocular disparity and the rate of change of size does not depend on viewing distance, but does depend on the linear width of the object and the observer's interpupillary distance. (From D. Regan & K. I. Beverley. Binocular and monocular stimuli for motion-in-depth: Changing-disparity and changing-size inputs feed the same motion-in-depth stage. *Vision Research*, 1979, 19. Reprinted with permission.)

allowance for geometric factors, the ratio of the effectiveness of stereoscopic and changing size stimulation is about 0.28 for this subject; after allowance for geometry, the binocular stimulus of changing disparity would be about 1.5 times more effective than changing size as a stimulus for motion in depth of this narrow object. Of course, this applies only to one particular subject, and relative effectiveness would have to be computed for other subjects on an individual basis.

Figure 19.22 compares the effectiveness of brief unidirectional changes of size and disparity in producing the sensation of motion in depth. As noted earlier, oscillations in the size of a bright square can give rise to two different sensations: motion in depth and changing size. Figure 19.24 compares the effectiveness of changing size in producing each of these sensations as a function of frequency of size oscillation. Changing size is ineffective as a stimulus for motion in depth at frequencies above about 3 Hz. However, at frequencies of 3–5 Hz the subject can detect a change in size without experiencing a change in depth.

2.2.4.3. Motion in Depth and Motion in the Frontal Plane. The effects of oscillation frequency on the perception of motion in depth and motion in the frontal plane were compared in Figure 19.18(a) and (b). Both the left eye's target and the right eye's target oscillated from side to side. The only difference between the binocular stimulus in (a) and the stereoscopic stimulus in (b) is that the left and right eyes' oscillations were inphase in (a) and in antiphase in (b). It is clear that sensitivity to motion in depth due to oscillating disparity falls off at a lower frequency of oscillation than does sensitivity to motion in the frontal plane caused by oscillating position [binocular in (a)]. A similar difference was also found for motion in depth due to changing size (see Figure 19.24). To summarize, motion in depth caused by change in disparity and motion in depth caused by change in size both collapse at frequencies in excess of about 3 Hz, but the subject continues to perceive motion in the frontal plane at much higher frequencies.

2.2.4.4. Comparison of Static Disparity and Changing Disparity. Regan and Beverley (1973) suggested that responses

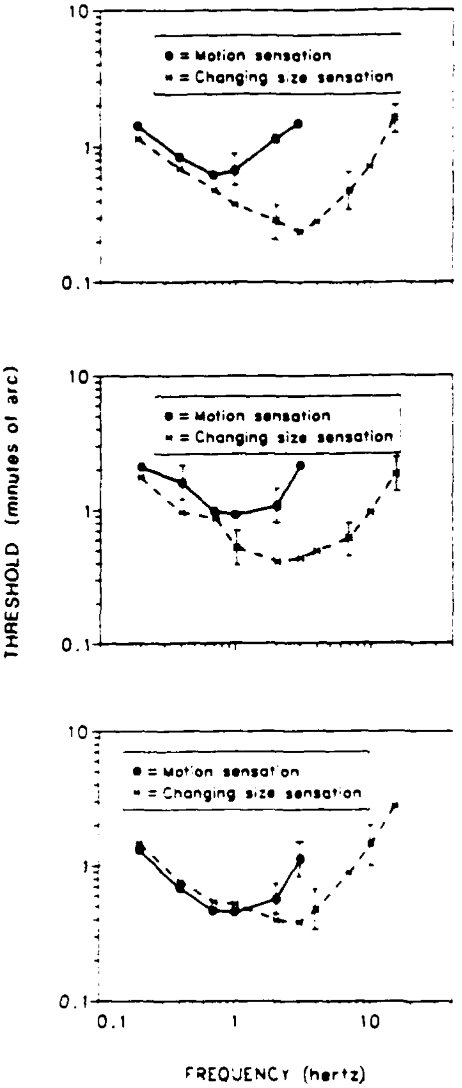


Figure 19.24. Effect of frequency of size oscillation on perception of motion in depth and changing size. The stimulus was a solid bright square (mean size 0.5° on a side) that alternately expanded and contracted in size at different oscillation rates. Subjects were instructed to set the amplitude of the size change to make the motion in depth barely visible on some trials and to make changing size just visible on other trials. Solid curves show the *minimum oscillation amplitude (in minutes of arc) that produced a sensation of motion in depth*; dashed curves, the minimum oscillation amplitude that produced a sensation of changing size. Data are from three different subjects who viewed the stimuli binocularly. Vertical lines indicate ± 1 SD. Motion in depth sensation fails above about 3 Hz, but the sensation of changing size persists to above 10 Hz. (From D. Regan & K. I. Beverley, Binocular and monocular stimuli for motion-in-depth: Changing-disparity and changing-size inputs feed the same motion-in-depth stage. *Vision Research*, 1979, *19*. Reprinted with permission.)

to changing disparity are fundamentally different from responses to static binocular disparity. One reason for this is that stereoscopic sensitivity to motion in depth cannot be predicted from acuity for static relative disparity.

As pointed out earlier, the direction of stereoscopic motion in depth is indicated by the stimulus velocity ratio V_L/V_R (Figure 19.15). However, classic stereoscopic depth perception is related to the positional disparities of the half-images on the two retinas. The two are not equivalent because a given rate of change of disparity corresponds to an indefinite number of values of V_L/V_R. Furthermore, the binocular disparity of any given object is different for different angles of ocular convergence, because disparity is measured relative to the frontal plane passing through the point of binocular convergence and thus relates not to absolute depth but rather to depth relative to this plane.

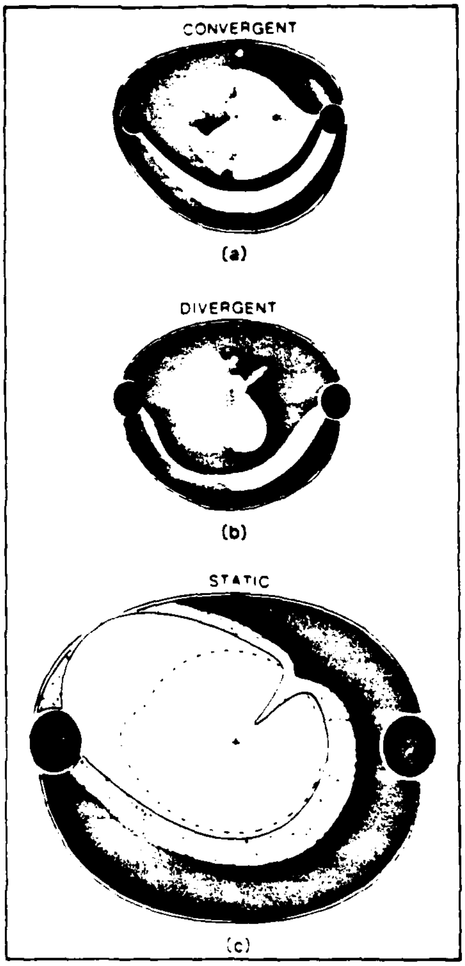


Figure 19.25. Visual fields for static stereoscopic depth and for stereoscopic motion in depth. Data were collected using Richards' (1972, 1977) technique of stereoperimetry. In this method, the cross-polarized half-images of a 1° bar were projected onto a screen and viewed by the subject through Polaroid spectacles. To measure sensitivity to motion in depth, a continuously visible bar was oscillated in depth between 0 and 0.4° convergent or divergent disparity. To measure sensitivity to static disparity, the bar was presented with 0.4° divergent or convergent disparity for 100-msec exposures. The blind spots corresponding to the positions of the optic disk in the two retinas are represented by the outlined circular areas on both sides of the portrayed visual fields. The dark regions of map (a) are areas in the visual field that were "blind" to the motion in depth with convergent disparity. Stippled areas show where unstable depth sensations could sometimes be elicited. Panel (b) shows a similar map for motion in depth in a divergent direction. Both maps differ substantially from map (c), where the solid curve encloses the region in which the subject could correctly estimate the position in depth of a stationary bar. Comparison of (b) and (c) shows that some areas of the visual field are "blind" to motion in depth but still are sensitive to static disparity, and vice versa. (From W. Richards & D. Regan, A stereo field map with implications for disparity processing, *Investigative Ophthalmology*, 1973, *12*. Reprinted with permission.)

In contrast, the value of V_L/V_R is approximately the same for different angles of ocular convergence. The origin of the coordinates of disparity-based geometry varies with the point of convergence, whereas the coordinates of V_L/V_R geometry are fixed in the head.

Evidence that physiological responses to disparity and to V_L/V_R are different comes from the finding that the visual fields of many observers contain regions that are "blind" to stereo motion in depth but not to the classic static disparity and vice versa (Richards & Regan, 1973). Figure 19.25 shows a visual field of this type. The subject had normal visual acuity and perimetric examination revealed no scotomas. The white areas in Figure 19.25(a) and (b) show where the subject could see the motion in depth of a bar that oscillated back and forth in depth. Outside these areas the subject was essentially blind to motion in depth. Figure 19.25(c) shows the regions where the subject could accurately judge the position in depth of a stationary bar. Areas that were blind to motion in depth differ in location from areas that were blind to static disparity. Apparently, it is fairly common for stereo fields to contain areas blind to motion in depth, even in normally sighted individuals. However, the locations of these "motion blind" areas seem to be peculiar to the individual. In any event, the conclusion is that the neural mechanisms subserving sensitivity to static disparity and to kinetic disparity are sufficiently separate that one can be impaired and the other spared.

Richards' and Regan's findings suggest that subjects who have extensive areas of the visual field that are "blind" to stereoscopic motion in depth might misjudge the trajectories of objects in the affected areas of the visual field. However, because changing size is an additional stimulus for motion in depth, it could offset the effects of "blindness" to changing disparity. Confirming this suggestion, Regan and Beverley (1983a) found that sensitivity to changing size was normal in regions of the visual field of a subject that were blind to changing disparity.

Cynader and Regan (1978, 1982) found neurons in area 18 and in the 17/18 border of the cat that were selectively sensitive to the ratio between left and right retinal image velocities. In other words, these neurons were tuned to the direction of motion in depth. Some of the most sharply tuned neurons fired most briskly when the retinal images moved in opposite directions, corresponding to a range of directions spanning no more than 1–2°. Some of these neurons maintained their directional tuning over a fourfold range of speeds [Regan & Cynader, 1982; Figure 19.26 (a)]. A second class of neuron fired best for trajectories that missed the head. These were tuned to a broader range of directions than the "hitting the head" class of neurons.

Cynader and Regan (1978) found that the well-known "binocular depth" class of neurons is also very selectively sensitive to the direction of motion in depth. These neurons show strong interocular facilitation (up to 100-fold) when motion is accurately parallel to the frontal parallel plane [Figure 19.26(b)]. However,

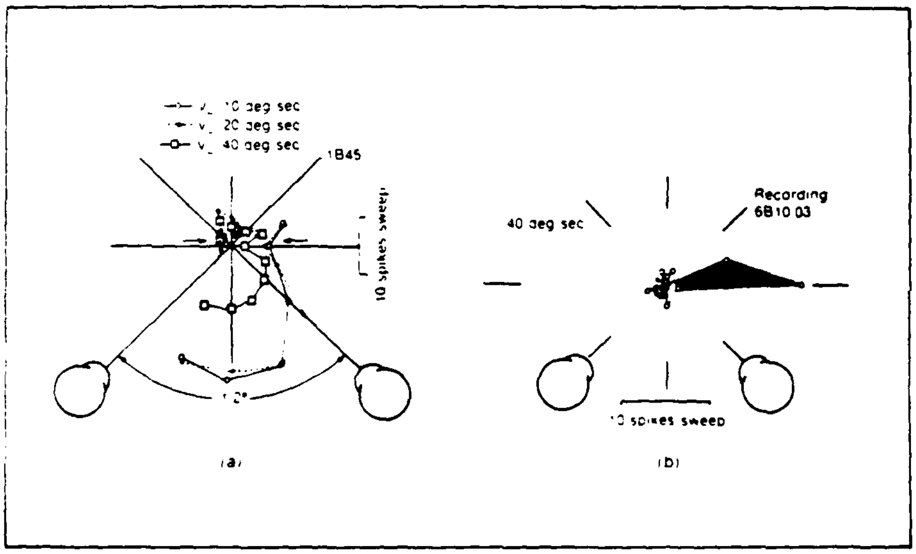


Figure 19.26. Selective sensitivity of neurons in the visual cortex of the cat to direction of motion in depth. Number of spikes per unit time is plotted radially as a function of the direction of motion in depth. The ratio of retinal image velocities (V_L/V_R) is plotted as azimuthal angle. This scale exaggerates the cone of angles subtended by the eyes. Panel (a) shows the response properties of a "hitting the head" neuron. This cell fired strongly to binocular stimulation only when the test bar moved along a path of collision with the right side of the head. Strong firing was restricted to a cone of directions about 1.0° wide. The cell maintained its sharp selectivity even when stimulus speeds were doubled and redoubled. This unit's selectivity was achieved by interocular inhibition, as indicated by the arrows. Panel (b) shows a unit that fired at an appreciable rate only when (1) the target's disparity was near zero, (2) its direction of motion was closely parallel to the frontal plane in a left-right direction, and (3) vision was binocular. Closed circles show firing when the two eyes were stimulated separately, and open circles show firing with binocular vision. The black area marks the very strong interocular facilitation observed with binocular vision. (From D. Regan & M. Cynader, Neurons in cat visual cortex tuned to the direction of motion in depth. Effects of stimulus speed. *Investigative Ophthalmology and Visual Science*, 1982, *22*. Reprinted with permission.)

the chief property of this type of neuron is its comparatively sharp tuning to disparity, that is, to relative position in depth. It was suggested that the first two classes of neuron are involved in the perception of stereoscopic *motion* in depth (Cynader & Regan, 1978); the third class, it has been suggested, is involved in the perception of relative *position* in depth (Barlow, Blakemore, & Pettigrew, 1967). Extrapolating to human vision, these "motion-in-depth" and "position-in-depth" neurons provide a possible physiological basis for findings such as selective "blindness" for motion in depth while visual sensitivity to position in depth is preserved and vice versa (Figure 19.25).

Some of the first two classes of "motion-in-depth" neurons maintain their tuning to the direction of motion in depth over a range of disparities as wide as 12° (Cynader & Regan, 1982). Other neurons of the first two classes systematically change their tuning as a function of disparity, for example, by favoring motion towards the plane at which the eyes are converged (the plane of fixation) for objects that lie either nearer or farther than the plane of fixation.

3. THE DIRECTION OF SELF-MOTION IN DEPTH AND OPTIC FLOW PATTERNS

Studies on visual cues to self-motion encompass several different problems. Some investigators are concerned with the sensation of self-motion that can be produced by visual stimulation. For example, when sitting in a stationary train parked next to a moving train, one may perceive the outside world as stationary and oneself as in motion (Dichgans & Brandt, 1978). Peripheral retinal stimulation is particularly effective in generating this illusion, and even a small area of peripheral stimulation can be effective (Brandt, Dichgans, & Koening, 1978; Johansson, 1974). The discussion here does not treat the sensation of locomotion caused by visual stimulation, but is restricted to a different problem: what visual cues are used for accurate visual guidance of locomotion.

Changing size and changing disparity are potentially of help in guiding a person's locomotion, and it has been empirically shown that the use of visual cues to motion in depth is particularly important in landing an aircraft. Other sources of information that may be employed by a pilot include flow gradients of the terrain, perspective, and the angular distance between the horizon and an aim point on the ground.

3.1. Analysis of Visual Flow Patterns by the Human Visual System

As an observer moves through the external world, the location from which the world is viewed continually changes and, because the world is three-dimensional, what the observer sees is different from one instant to the next. This continuous change of viewpoint makes available information about the outside world that is not available in a view from a static position. An analogy with that famous medical instrument, the CAT scanner, might be useful here. Comparing many X-ray photographs of the brain taken from different angles provides information not available in one single photograph, and this comparison is performed rapidly and automatically by a computer using special-purpose algorithms. Turning back to self-motion, the brain might, in principle, parallel the CAT computer's ability to extract information by comparing views from different locations. Rather than operating on an ordered sequence of single "snapshots," however, the brain has available a continuous ordered flow of different views so that information about the outside world could, in principle, be extracted by means of specific visual sensitivities to different aspects of motion. Indeed, there is experimental evidence that the visual pathway does have several different motion sensitivities that would allow the extraction of visual information unavailable to a stationary observer. For example, depth perception can be generated by motion parallax (Graham & Rogers, 1982; Rogers & Graham, 1982). Camouflaged objects that are invisible in the absence of relative motion can be rendered visible by motion parallax alone (Anstis, 1970; Braddick, 1974; Foster, 1971; Poggio et al., 1983; Regan & Spekreijse, 1970; Reichardt & Poggio, 1979) by means of visual processing that is quite different from the processing involved in detecting noncamouflaged objects (Regan & Beverley, 1984b). Further to this point, evidence is discussed below that the visual pathway is sensitive to mathematical elements of the optic flow field such as divergence and curl.

Anticipating such recent empirical studies, in his seminal writings Gibson (1950) pointed out that the extra information potentially made available to an observer by self-motion includes visibility of three-dimensional camouflaged objects, and the three-dimensional relationships between external objects as well as the observer's direction of self-motion. Gibson's theoretical approach to this topic was via the concept of the "optic array." The optic array contains visual information that is potentially available to the observer. This information includes motion perspective and the focus of expansion in the flow of optical texture. Chapter 21 by Sedgwick describes the Gibsonian concept of the optic array, and the concept is also briefly discussed by Hochberg in Chapter 22. For present purposes, it suffices to follow Gibson (1979), who defined the ambient optic array at a point of observation as a "nested set of adjacent solid angles . . . [where each solid angle corresponds to] one of the large facets or small facets of the environment. The solid angles are separated by contours or contrasts" (Gibson, 1979, p. 310). Thus the optic array is the set of all possible retinal images of a scene projected onto the picture plane.

Recent theoretical work on visual flow patterns has included attempts to represent the flow pattern as a velocity field that is completely described by assigning a magnitude (i.e., speed) and direction to every point in the field. Several authors have sought to describe this vector field in terms of the vector calculus notation conventionally used to describe vector fields such as electrical fields and the field of local velocity in flowing water (Gordon, 1965; Koenderink & van Doorn, 1976, 1981; Longuet-Higgins & Prazdny, 1980; Prazdny, 1980). In these terms the flow pattern can be analyzed into mathematically independent elements that include the divergence, curl, and gradient of velocity at each point in the field (i.e., div V, curl V and grad V respectively; see Appendix). At an intuitive level, these mathematical quantities can be understood in terms of the flow pattern in an emptying bath. The divergence of surface velocity (i.e., div V) is large near the drain hole where div V expresses the loss of water. The curl of surface velocity (i.e., curl V) is large where there are vortices in the water. Longuet-Higgins and Prazdny (1980) conjectured that the visual pathway might have evolved neural mechanisms that were specifically sensitive to these mathematically independent quantities. They pointed out that the "looming detectors" of Regan and Beverley (1978b) can be regarded as roughly approximating detectors for div V.

Further support for their conjecture is provided by a recent suggestion that the visual system is specifically sensitive to a rough approximation of vorticity or curl V (Regan & Beverley, 1984a). The problem addressed by this study was whether visual responses to rotary motion can be explained in terms of the known sensitivity to linear motion. The rationale of the experiment is illustrated in Figure 19.27.

Subjects were adapted to one of two circular areas of moving dots, divided into quadrants. The dots in each quadrant oscillated back and forth linearly. In one stimulus pattern, the dots in all quadrants moved "clockwise" or "counterclockwise" together, providing a strong rotary component of motion about the center, although no individual dots actually moved along a curve [Figure 19.27(a)]. In the other pattern, dots in two opposite quadrants moved "clockwise" whereas those in the other two quadrants moved "counterclockwise," so that no rotary motion component was present [Figure 19.27(b)]. After adapting to these patterns, subjects viewed a test circle of random dots that rotated about its center [Figure 19.27(c)]. It was envisaged that a curl (i.e., vorticity) mechanism might be adapted by Figure 19.27(a) but would not be adapted by Figure 19.27(b). On the other hand, (a) and (b) would have identical effects on linear motion mechanisms, for the dot motion within any quadrant was identical in the two stimuli.

After viewing one of the adapting patterns for 5 min, subjects set the test pattern to the smallest rotary oscillation that could just be seen. Base-line thresholds were established after adapting to a stationary dot pattern. The main finding was that stimulus (a) produced threshold elevations up to 600% greater than stimulus (b). This difference was greatest when oscillatory frequency was about 4–6 Hz. Arguing that this difference could not be explained in terms of visual sensitivity to linear motion, Regan and Beverley (1984a) concluded that the visual system is specifically sensitive to rotary motion. They went on to suggest that the visual system contains detectors sensitive to some rough approximation to curl V.

3.2. The Direction of Self-Motion in Depth

Gibson (1950, 1979) pointed out that, when an observer moves forward, the optic array (see above) contains a radially expanding flow pattern, and the focus of expansion coincides with the moving observer's destination in the outside world. The focus of expansion in the optic array is potentially available as a guide to self-locomotion. Going further, Gibson (1958) suggested that humans and animals can, in practice, use the focus of expansion in the optic array to guide self-locomotion. This prediction is, of course, open to experimental test.

First, it should be noted that the flow pattern in the optic array is not necessarily the same as the flow pattern in the retinal image. This happens, for example, when moving observers do not look at their destination or gaze at a fixed angle to their destination, but rather look at some nearby feature in the world. In this important case, their eyes rotate continuously and add to the radial expansion pattern a translational velocity of the whole retinal image. This changes the flow pattern, and the focus of expansion may be displaced so that it no longer coincides with the destination. In other cases the focus may be abolished altogether (Koenderink & van Doorn, 1976; Regan & Beverley, 1982; Richards, 1975). A specific example in which the focus of expansion does not coincide with the destination is illustrated in Figure 19.28. Figure 19.28(a) represents the focus of expansion in the optic array. This differs from the flow pattern on the retina [Figure 19.28(b)] when the eye moves to track a point (B) on a vertical surface toward which the observer is moving. It is clear that in this special instance there is a flow outward from the impact point A in Figure 19.28(a). Figure 19.28(c)–(e) illustrate this with photographic multiple exposures. In (c) the camera is moving toward the nose and pointing at the nose; this illustrates the flow pattern in the optic array. In (d) the camera is moving toward the nose, but pointing at the arrowed dot. Can a subject separate the translational flow introduced by the eye movements from the radial flow in the optic array and respond to the latter? Although the expanding component and the translational component due to eye rotation "are, in principle, separable" (Lee, 1976, p. 140), it is an empirical question whether or not the visual system can separate them in practice. Experimental evidence on this point includes Regan and Beverley's (1982) demonstration that in at least one situation observers are not able to separate the effects of one-dimensional

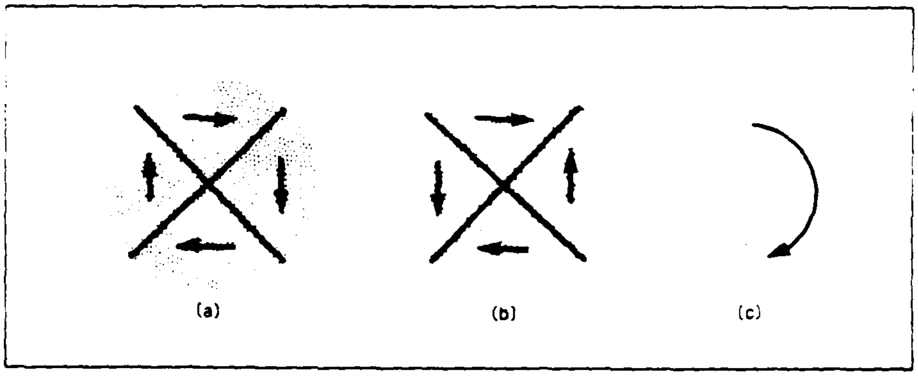


Figure 19.27. Adaptation to rotary motion (a) and (b) were adapting patterns consisting of a 2° diameter area of random dots divided into four quadrants. Dots in any given quadrant oscillated sinusoidally along a straight line at the same frequency and with the same peak-to-peak amplitude of 1°, but the directions of oscillation were different for the four quadrants. Adapting stimuli (a) and (b) differed only in the relative phasing of the quadrants, as shown by the arrows. In (a) all dots moved clockwise or counterclockwise together, so the circular disk had a strong rotary component of motion about the center. In (b) the relative phasing of the quadrants gave the disk a zero net rotary component of motion about the center. Test stimulus (c) was a 1° diameter area of random dots that rotated sinusoidally to and fro about the center with an amplitude adjustable by the subject. Adaptation to (a) had a much greater effect on sensitivity to the rotary motion of the test stimulus than did adaptation to (b) (Regan & Beverley, 1984a).

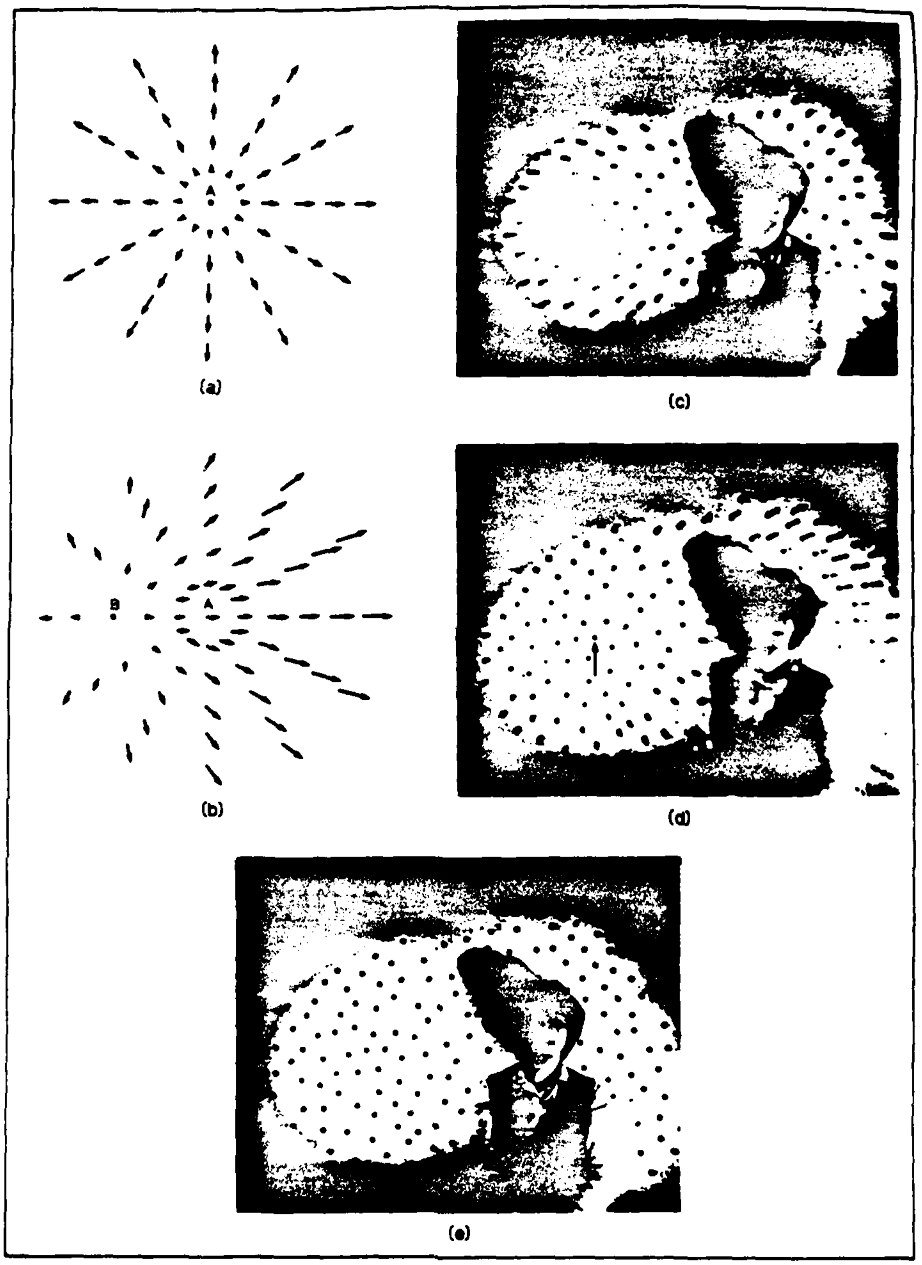


Figure 19.28. Expanding flow patterns with direction of gaze at focus of expansion and with direction of gaze off to one side. In pattern (a) the observer's gaze is fixed at the focus of expansion at A, and all elements of texture in the image of the surface expand away from this focus. This symmetrical expansion pattern occurs in the optic array and also in the retinal image when the direction of gaze remains fixed at the point of impact with the surface. The surface in (b) is identical to the surface in (a) except that the observer fixates on point B rather than on the actual impact point A. This introduces a sideways component of motion in the image at point A. In both patterns, for simplicity, the rate of change of magnification is the same for all points in the field of view. Photograph (c) is a multiple exposure taken with the camera moving toward the head and always pointing at the head. The center of expansion of flow coincides with the point toward which the camera is both moving and "gazing." Photograph (d) is a multiple exposure of the same scene, but the camera is pointing at the arrowed dot while moving toward the head. This corresponds to the situation depicted in (b). Photograph (e) is a single exposure of the scene in (c) and (d). (From Regan & Beverley, 1982.)

translational flow from expansion in order to locate the focus of expansion. This and other experimental evidence are discussed below.

First, let us consider situations in which observers can use the center of expansion in the optic array to guide locomotion. As an observer moves along a straight-line path in space the texture of the terrain projected onto the frontal plane undergoes a time-varying transformation. As shown schematically in Figure 19.29, if the observer is the pilot of an airplane that is descending toward the ground on a straight flight path, a single point (the projected impact point) remains stationary in the optic array. However, this is true for the retinal image only if the observer gazes at the impact point or if the gaze is maintained at a fixed angle to a distant point. Provided one of these conditions is met, all other points in the retinal image move away from the impact point. Thus the terrain becomes magnified in such a way that all points retreat radially from the focus of expansion. The rates are higher for points in the lower part of the visual field than for those near the impact point. Rate also increases (accelerates) with distance upward of the impact point on the projection plane, but then the rate becomes smaller with further distance upward until it diminishes to zero at the horizon (see Figure 19.29). Thus the aim point (focus of expansion) in the optic array is a precise indicator of the momentary place of impact. Moreover, changes in the position of the focus of expansion correlate perfectly with changes in the flight path.

As implied above, although the foregoing account is correct geometrically, there is no direct evidence that observers can use the focus of expansion with the same precision under all possible stimulus conditions. At the very least, there must be some zone of confusion in detecting the precise position of the aiming point. Furthermore, as illustrated in Figure 19.28, translational flow may be introduced in the retinal image by eye movements toward one side of the impact point, and this may interfere with the detection of the center of expansion.

In any case, many factors require additional study. One is the role of inhomogeneities of texture in the visual field. Another is the amount of texture that is visible to the observer. The magnitude of the flight path angle, the distance between the observer and the impact point, "visual noise" or jitter introduced by turbulence, and the crab angle of the aircraft due to wind may also affect the detection of the focus of expansion by an aircraft pilot. So, for practical reasons, it is not sufficient simply to point to the invariant relationship between properties of the optic array and the motion in depth of the observer. Unfortunately, too little experimental work has been done on this problem.

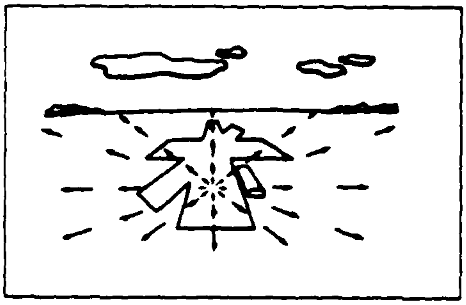


Figure 19.29. Expanding flow pattern in the optic array during final approach of an aircraft landing at an airfield. The focus of expansion in the optic array is the impact point of the aircraft provided it continues along the same path, though as shown in Figure 19.28, this is not necessarily the case for the retinal-image flow pattern. (From James J. Gibson, *The perception of the visual world*. Copyright 1950, renewed 1977 by Houghton Mifflin Company. Reprinted with permission.)

3.3. Experimental Studies of the Focus of Expansion

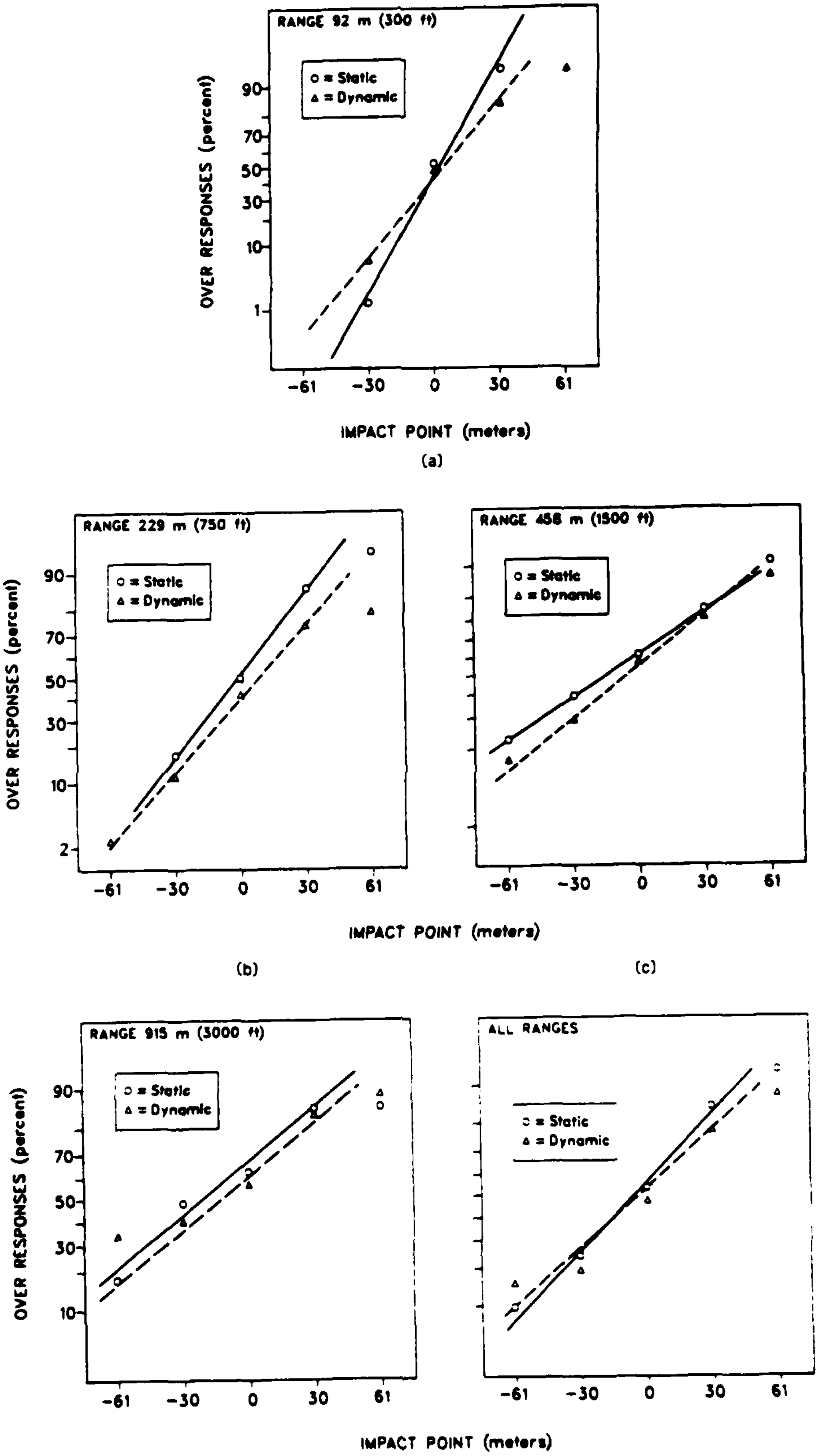
3.3.1. Simulated Aircraft Carrier Landings. Kaufman (1964) utilized a shadowgraph technique to study the sensitivity of observers in detecting the aim point in simulated landing of an aircraft on an aircraft carrier. In one experiment, subjects viewed a scene in which the aircraft approached a carrier deck at a simulated speed of 118 knots. The glide slope was held constant at 5°. Five glide paths were used: one intercepted the deck at the "correct" aim point (in the middle of the arresting cables), and the others at different distances either fore or aft of the correct aim point. All approaches began from an equivalent distance of approximately 1983 m from the desired aim point on the deck and closed to one of four ranges from 915 to 92 m away from the aim point. Viewing was restricted to the time the image was in motion.

Subjects were given a training period in which descents to the deck were simulated with subjects in control of their flight path. Subjects then observed each simulated approach segment and were instructed to judge the projected point of impact with the deck. The choices given the subject were "on," to indicate an aim point at the desired position on the deck; "short," to indicate landing too low in the projection plane; and "high," to indicate an overshoot of the desired aim point. Judgments were also made under static conditions in which the carrier deck was viewed from equivalent distances.

Data are shown in Figure 19.30. Static sensitivity is equal to or higher than dynamic sensitivity for all but the 458 m range. The biases are small—8 m or less—and variable, for all ranges.

When static and dynamic data are combined (Figure 19.31), it is evident that sensitivity increases with decreasing range. Thus at the shortest range of 92 m, subjects are able to judge the position of the aim point with an accuracy of about + 17 m, whether they see an expanding pattern or not. Clearly, cues other than the focus of expansion were being used by subjects in this experiment. Nevertheless, these results do not prove that subjects cannot use the focus of expansion to determine the impact point when no other cues are present. Several follow-up experiments were performed to determine more precisely what cues the subject was able to use. In one the aircraft carrier was replaced by a pattern of random dots toward which the subject made simulated approaches from 1983 m along straight-line glide paths ranging from 224 to 1464 m in length. In half the trials a horizon was present, but it was absent in the other half of the trials. The subject viewed the scene through an artificial pupil, as in the previously described experiment. The presence or absence of a horizon made no difference to accuracy of performance. The angular size of the vertical error in detecting the aim point was 1.5°, which corresponds to a very large linear error at all of the distances at which the judgments were made, for example, about 24 m at a range of 92 m, and proportionately larger at longer distances. In fact, an error of such magnitude would be intolerable in an actual flight situation.

In still another experiment, the aircraft carrier was present, but the textured background was eliminated so that the subject saw the deck from a distance in a uniform dark gray "sea."


RANGE 92 m (300 ft)
○ = Static
△ = Dynamic
OVER RESPONSES (percent)
90
70
50
30
10
1
-61
-30
0
30
61
IMPACT POINT (meters)
RANGE 229 m (750 ft)
○ = Static
△ = Dynamic
OVER RESPONSES (percent)
90
70
50
30
10
2
-61
-30
0
30
61
RANGE 458 m (1500 ft)
○ = Static
△ = Dynamic
-61
-30
0
30
61
IMPACT POINT (meters)
RANGE 915 m (3000 ft)
○ = Static
△ = Dynamic
OVER RESPONSES (percent)
90
70
50
30
10
-61
-30
0
30
61
ALL RANGES
○ = Static
△ = Dynamic
-61
-30
0
30
61
IMPACT POINT (meters)

(a)

(b)

(c)

(d)

(e)

Performance was no different under these conditions than in the first experiment.

It is clear from these experiments that time-varying changes in texture were not used by subjects in detecting the impact point. Static perspective information given by the texture was not used by subjects either. In fact, when it was available, subjects used configurational information inherent in the scene. In this particular situation it was apparent that subjects could judge the aim point solely on the basis of the ratio of the vertical angles subtended by the stern and the deck of the aircraft carrier (see Kennedy, Collyer, May, & Dunlap, 1982; and Kruk & Regan, 1983, for a similar discussion regarding recognition of aircraft shapes). When the constant flight path is such that the impact point is too low, the stern is large relative to the deck. The reverse is true when the impact point is too high. Subjects seem to detect this without specific training or instructions. This cue does not exist except in situations similar to that investigated in these experiments, but it should alert us to the fact that even when the eye is fixed and the scene is viewed through an artificial pupil, the focus of expansion can be detected only with limited accuracy and that other information, when available, may be used. Llewellyn (1971) reached a similar conclusion using a quite different stimulus pattern.

3.3.2. Effects of Translational Motion of the Retinal Image on Use of Focus of Expansion. The flow pattern in the optic array may differ considerably from one situation to another, depending on the nature and locations of surfaces in the environment. Several discussions that bear on this point are available (Gordon, 1965; Koenderink & van Doorn, 1976, 1981; Lee, 1976; Lee & Lishman, 1977; Nakayama & Loomis, 1974). In addition, eye movements may cause the flow patterns in the retinal image and the optic array to be different, as noted earlier. For example, when an observer gazes at an object to one side of the impact point, the eye rotates and a uniform translational velocity of the whole retinal image is superimposed on the expanding flow pattern, as illustrated in Figure 19.28(a) and (b).

Regan and Beverley (1982) compared subjects' ability to locate the focus of expansion of a flow pattern when a translational velocity was impressed on the whole pattern, and when there was no translational velocity. To isolate the expanding flow pattern from other stimulus variables (such as div V) they chose a flow pattern similar to that produced by a zooming lens; that is, the rate of increase of magnification was the same at every point in the pattern. In Regan and Beverley's (1982) three experiments the target was a grating of vertical bars whose magnification continuously increased so that it expanded horizontally (Figure 19.32). Total stimulus field size was constant. In Experiment 1, translational velocity was always zero. A black reference bar was located at the center of the pattern. In successive trials the center of expansion was located at different distances to the left or right of the reference bar, and the subject's task was to judge left or right. Subjects found the laboratory task easy, and could locate the center of expansion to better than 1°. In this condition, with no translational velocity, any given trial was equivalent to the real-world situation of a subject's gazing at a fixed angle relative to the impact point as, for example, when a car driver gazes at a fixed angle relative to the car body while the car travels the way it is pointing.

The finding is consistent with Gibson's (1950) estimate of about ± 1° for the accuracy with which subjects could judge the impact point when viewing movie films taken from a fixed camera on an aircraft during landing. (If we regard the movie camera as an eye aligned at a fixed angle relative to the aircraft and assume that the aircraft maintained a fixed orientation relative to its trajectory, then the two stimulus situations are geometrically similar.) Such measurements may have some practical interest in that they estimate how accurately subjects use the focus of the expanding flow pattern to estimate the direction of self-motion in the special case where the eye is pointing at the impact point or maintains a fixed angle relative to the impact point. But this experiment does not address the question of how accurately subjects can use the focus of the expanding flow pattern in the general case of arbitrary direction of gaze.

Regan and Beverley (1982) attempted to address this question in their second experiment. Experiment 2 resembled Experiment 1 except that horizontal translational velocities were added to the stimulus pattern so as to mimic the effect of slow pursuit eye movements. As illustrated in Figure 19.28(b) and (d), the effect of gazing at an object to one side of the impact point is to impress a uniform translational velocity on the whole

Figure 19.30. *(Opposite)* Perception of point of impact for simulated aircraft carrier landings. Subjects saw expanding scenes of a carrier deck that simulated the viewpoint of an aircraft approaching the carrier at a speed of 118 knots along one of five glide paths intercepting the deck at different impact points. Glide slope was constant at 5°. All approaches began from a distance of 1983 m and closed to a range of 915, 458, 229, or 92 m. Subjects judged whether the aircraft would undershoot, overshoot, or land right on the correct aim point in the middle of the arresting cables. The five panels are psychometric functions plotted on probit paper which give the probability of judging that the aircraft would overshoot the desired aim point as a function of the actual miss distance (negative values represent undershoot; positive values, overshoot). (For analysis, "on" judgments were distributed equally among undershoot and overshoot categories.) In each panel, the stimulus condition corresponding to 50% probability of an "over" response represents the response bias. The slope of each line is a direct measure of variability and represents the standard deviation. In panels (a)–(d), the dynamic condition (solid line) is data obtained after viewing the simulated scene throughout the entire descent of the aircraft from the starting distance to the range given at the top of each panel. The static condition (dotted line) represents the same function obtained when the subject viewed only a static scene of the carrier deck from the range given. Data are based on 190 trials per subject, averaged across four male subjects with normal vision who viewed the scenes through an artificial pupil. *Panel (e) shows data combined over all ranges. Performance did not differ significantly* for the static and dynamic conditions. Thus it appears that subjects did not use the information provided by the expanding texture in the display, but employed configural information that was inherent in the static scene. *(From Kaufman, 1964.)*

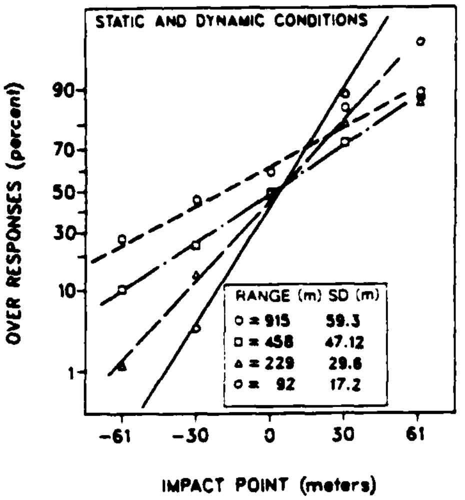


Figure 19.31. Effect of range on judgment of impact point for simulated aircraft carrier landings. Data for the static and dynamic conditions of the carrier landing task portrayed in panels (a)–(d) of Figure 19.30 were combined, and the resulting psychometric functions are superimposed here. The increase in the slopes of the psychometric functions as the range at which judgments are made decreases provides graphic evidence that the sensitivity of subjects to deviations from the actual aim point increases monotonically in linear distance as range is shortened; this is to be expected for a constant angular error of about 1.5°. (From Kaufman, 1964.)

retinal image. Regan and Beverley found that adding translational velocity severely reduced subjects' ability to locate the focus of expansion: accuracy fell from better than 1° to a level where subjects' responses were essentially random and accuracy could not be reliably estimated, but was considerably worse than 10°. Extrapolating to real-world conditions, Regan and Beverley suggested that in the general situation where the eye is not maintained at a fixed angle relative to the impact point so that overall translational motion is added to the expansion pattern, subjects cannot accurately locate the focus of expansion. It should be noted that rough estimates of the direction of self-motion are a different matter. Richards (1975) calculated that gazing to one side of the impact point creates an asymmetry in the flow pattern that is particularly evident when a very wide field of view is provided, and points out that this asymmetry might be used to estimate roughly the impact point to an accuracy of 10–20°. This accuracy would seem far inferior to that required for precise self-location.

A different kind of flow pattern was used in Regan and Beverley's (1982) third experiment. This flow pattern had a center of expansion as in Experiment 2, but also had a local region where div V was larger than elsewhere on the pattern. In other words, the rate of increase of magnification was not uniform over the whole pattern, being larger in a local region than elsewhere. The point of this experiment was that eye movements can disturb the expansion pattern and shift its focus, but do not affect the location of the point where div V is maximal. (A uniform translational velocity does not affect the magnification at any point in the pattern.) Experiment 2 was repeated using several different expansion patterns. In some the rate of increase of magnification was very different at different points in the pattern; in others the rate of increase of magnification was almost uniform over the pattern. Figure 19.33(a) formally describes three of these different patterns. Instantaneous velocity of any point in the pattern was a power function of distance across the screen for all expansion patterns. Different patterns had different exponents. Figure 19.32 shows the flow pattern when translational velocity was set to zero. The maximum rate of increase of magnification was the same for all patterns. A real-world equivalent is the maximum rate of expansion seen from an automobile traveling at 55 km·hr^{-1} directly at a wall 81 m away. The straight line with exponent $n = 1.0$ in Figure 19.33(a) represents the pattern used in Experiment 2 where velocity linearly increased across the screen so that the rate of magnification was uniform (i.e., div V was the same at all points on the pattern). For the pattern with exponent 0.3 in Figure 19.33(a), there was a very clear region in the pattern where div V was greater than elsewhere (see Appendix). Results for two subjects are shown in Figure 19.33(b) and (c), which plot subjects' accuracy in judging the location of the point where magnification increased fastest for several exponents n of the pattern. As noted in Experiment 2, accuracy was too poor to be measured when $n = 1.0$, and with $n = 0.9$ was still only 10° or so. However, for exponents less than about 0.8, subjects performed the task easily with an accuracy better than 1°, even when substantial translational velocities were imposed on the flow pattern.

Regan and Beverley's (1982) conclusion can be stated as follows. Subjects can accurately locate a local maximum of div V in a flow pattern, even in the presence of translational motion that virtually abolishes the ability to locate the focus of expansion in the same pattern.

This finding raises the question of whether the visual system's specific sensitivity to looming (Section 2.2.2 above) might be implicated in behavioral responses to flow patterns in the optic array. The basis for this supposition is, first, that specific sensitivity to looming can be regarded as a specific sensitivity to div V and, second, that the receptive fields involved in looming sensitivity seem to be smaller than about 1.5° diameter so that they are potentially capable of mediating accurate localization.

Regan and Beverley's (1979b) laboratory study is relevant to this point. In this experiment, subjects adapted to radial flow patterns, and the effect of this adaptation on sensitivity to changing size was measured. Subjects were instructed to aim their gaze at a fixed angle relative to the focus of expansion of a flow pattern [either 2.0° to the left of the focus, as illustrated in Figure 19.34(b) or, in different experiments, directly at the focus]. The test stimulus and the adapting stimulus are illustrated in Figure 19.34(a) and (b). The adapting stimulus was a pattern of short line segments that alternately moved radially away from a focal point and back toward it at constant radial speed. The individual line segments were lengthened and shortened in proportion to their distance from the focus, and the direction of flow was reversed at 5-sec intervals. As shown in Figure 19.34(c), adaptation to this flow pattern results in a loss of sensitivity to the changing size of a test square located near the focus.

The flow pattern used in this experiment has the property that div V is low except immediately near the focus, where it rises to a sharp maximum [see the Appendix and Figure 19.35(d)]. This line of argument leads to the prediction that findings would have been different if the velocity across the radially expanding pattern had not varied with an abrupt transition at the focus as shown by the continuous line in Figure 19.35(c), but instead had varied linearly across the screen as shown by the broken line. Such a pattern would have the same value of div V at every point on the pattern [broken line, Figure

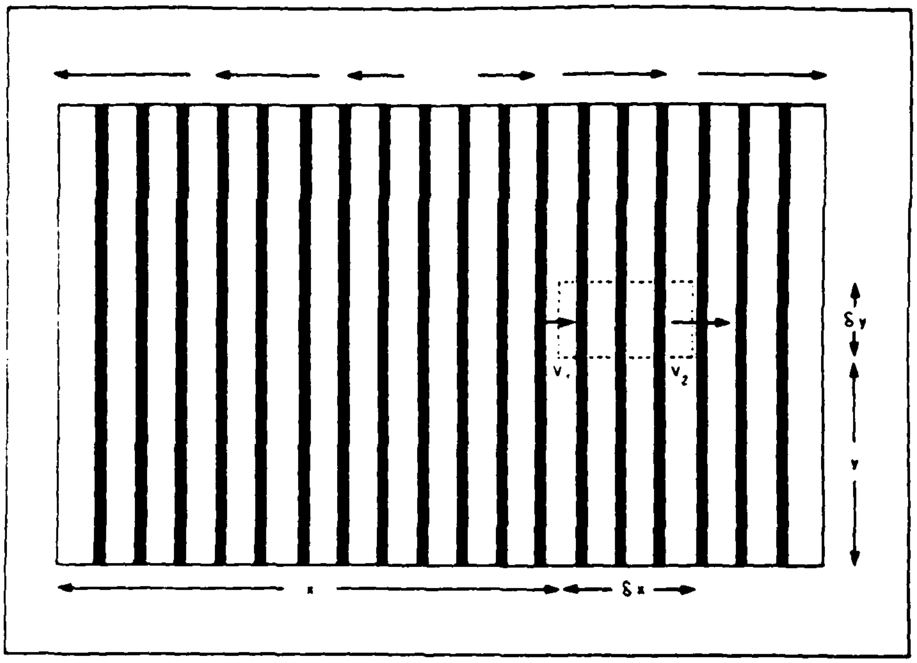


Figure 19.32. Expanding grating pattern used to study sensitivity to various cues to the direction of self-motion. The focus of expansion of the retinal flow pattern during self-motion depends on the direction of gaze and does not coincide with the direction of motion unless the observer is looking at the destination point (see Figure 19.28). However, in some (but not all) situations the point of maximum rate of change in magnification of the retinal image does coincide with the direction of self-motion and is independent of the direction of gaze. The grating shown here illustrates the type of stimulus used to study sensitivity to this local maximum in the rate of expansion in the flow pattern. The vertical grating expanded horizontally (thus changing in spatial frequency) as indicated by the arrows at the top of the figure. In addition, an overall translational motion was imposed on the pattern so that some predetermined point on the pattern simulated the point of gaze by becoming stationary. An arbitrarily small area of the grating (bounded by the rectangle and designated as dxdy) could be created whose vertical boundaries had velocities V_1 and V_2 that differed from the horizontal velocities of other points on the grating. Location of this area of maximum change in magnification rate was varied with respect to the focus of expansion of the grating to simulate the flow patterns that would arise during self-motion when center of gaze is shifted different distances away from the destination point. The subject's task was to locate the point of maximum rate of change in magnification. Figure 19.33 presents data showing that subjects were generally able to make this determination given appropriate rates of change in magnification at a local maximum.

19.35(d)]. This prediction is that changing-size threshold would be much less elevated than in the experiment of Figure 19.34(c), and that there would be no maximum at the focus. To date this prediction does not seem to have been tested.

Regan and Beverley's (1979b) conclusion was that visual mechanisms for looming would be strongly stimulated only near the focus of the flow pattern of Figure 19.34(b), that is, where div **V** is largest, and that these activated looming detectors would "mark" the location of the focus. Presumably, looming detectors would also "mark" the location where div **V** is largest in the Figure 19.33(a) patterns with exponents $n = 0.5$ and $n = 0.3$. Because visual sensitivity to changing size is not much affected by translational motion (Section 2.2.2.1), it seems possible that looming detectors could continue to "mark" the focus of the pattern in Figure 19.34(b) even if the pattern were moving *across the retina while expanding*. This could explain the finding [Figure 19.33(b) and (c)] that subjects could accurately locate the point on the expanding grating pattern where div **V** was largest, even when the pattern was in translational motion.

The foregoing hypothesis has not yet been subjected to definitive testing. However, sufficient experimental evidence has already been described to make such a conjecture seem more than merely plausible—for example, subjects can pick up the simulated impact point with considerable accuracy in cases where it is associated with nonuniformity in rate of change of magnification. On the other hand, the impact point does not necessarily coincide with the point at which div **V** is greatest: the two can be quite different (Regan & Beverley, 1982). Thus it is certainly not the case that the ability to visually locate the point of maximum div **V** can completely explain visually guided self-motion. The recent studies described above have suggested that the center of expansion is of limited value in guiding self-motion, but have not provided other than a limited alternative explanation.

Given that information for visually guided locomotion is computed from the optic flow pattern and eye movement data, the problem becomes to propose specific ways in which this might be achieved and to test these various hypotheses exper-

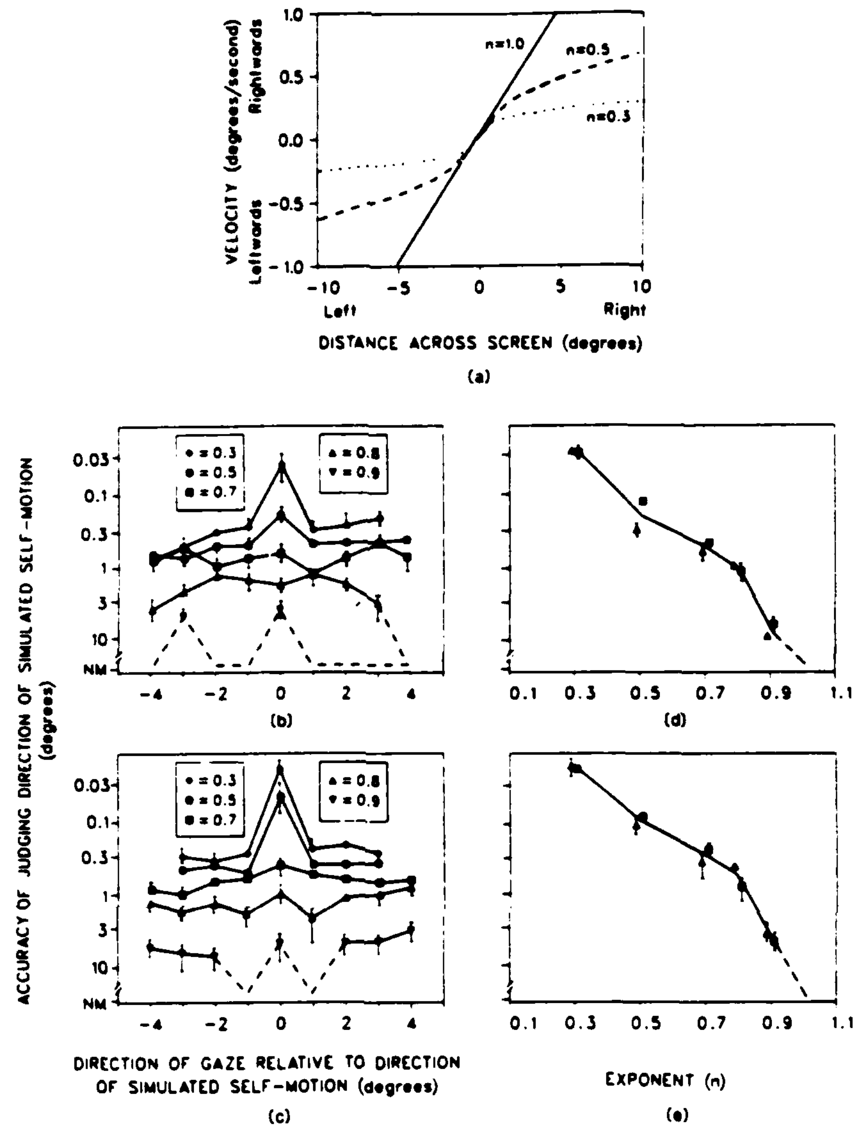


Figure 19.33. Relative usefulness of rate of change in magnification and center of expansion in judging the direction of simulated self-motion. Subjects viewed expanding grating patterns such as that shown in Figure 19.32. Panel (a) gives a formal description of the horizontal expansion of the gratings for three of the patterns used. The instantaneous velocity of any point in the pattern was first made a power function of distance across the pattern. Then a uniform translational speed was added that defined the point of gaze. The solid line in the graph represents the pattern in which the rate of change of magnification was uniform across the pattern ($n = 1.0$). The dashed line ($n = 0.5$) describes a pattern in which the rate of change in magnification was slightly greater at one point than elsewhere. This local maximum could be made more pronounced by adjusting the value of n, as in the dotted curve where $n = 0.3$. The rate of expansion in all cases was equivalent to impact with the target 5 sec after onset of stimulation. Initial spatial frequency was 5 cycles per degree; field size was 20° vertically and 12° horizontally. Each pattern presentation lasted 2 sec. For patterns with $n = 1.0$ (uniform expansion rate), the subject's task was to judge the position of the center of expansion, and for patterns with $n < 1.0$, subjects judged the position of the maximum rate of change in magnification. As shown in panels (b)–(e), when rate of change in magnification was uniform or nearly uniform over the pattern ($n = 1.0$ and $n = 0.9$) subjects could not perform the task at all. However, when the rate of change of magnification was appreciably greater at one point in the pattern than elsewhere, subjects were able to identify the local maximum almost independently of the direction of gaze ($n = 0.8$, $n = 0.7$). For $n = 0.5$ or $n = 0.3$, subjects were somewhat more accurate when the direction of gaze coincided with the direction of simulated self-motion. Panels (d) and (e) show how accuracy of judging direction of self-motion varied with the value of the exponent n when subjects were looking approximately along the direction of motion. The results suggest that the focus of expansion is not a generally useful cue to the direction of self-motion. The subject can locate a local maximum in the rate of change of magnification, but this does not provide a useful cue in all environments. (From D. Regan & K. I. Beverley. How do we avoid confounding the direction we are looking with the direction we are moving?, *Science, 215.* Copyright 1982 by American Association for the Advancement of Science. Reprinted with permission.)

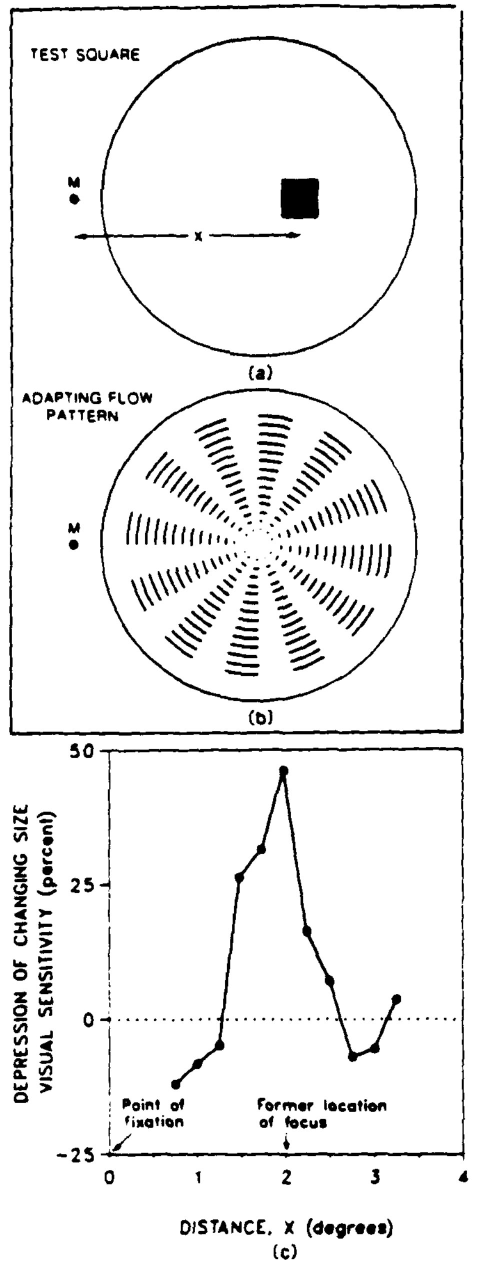


Figure 19.34. Reduction of looming sensitivity after adaptation to a radially expanding and contracting flow pattern. Panel (a) shows the test stimulus. Subjects fixated point M while viewing a square that oscillated in size at a distance X from the point of fixation. The smallest detectable oscillation in size was measured as a function of X. The adapting pattern is shown in (b). Subjects fixated on point M while the pattern alternately expanded and contracted for 5 sec each. After subjects viewed the flow pattern for 10 min, sensitivity to changing size was measured using the test pattern in (a). Graph (c) illustrates the effect of this adaptation on the threshold amplitude of size change as a function of the square's distance X from the fixation point. Sensitivity to oscillating size was sharply depressed when the square was in a region within about 0.5° of the focus of the radially expanding and contracting flow pattern. No such decline was found in a control study where the test square oscillated from side to side rather than oscillating in size. Thus the center of this expansion pattern can be located by means of sensitivity to changing size. (From D. Regan, K. I. Beverley, & M. Cynader. The visual perception of motion in depth. *Scientific American* 1979, *241*. Reprinted with permission.)

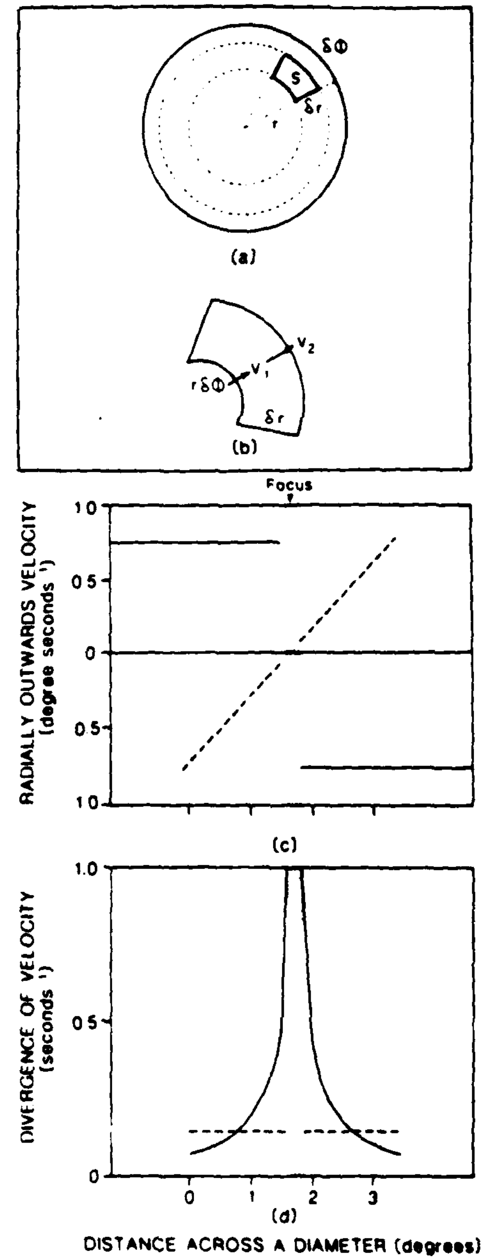


Figure 19.35. Velocity characteristics of radially expanding flow pattern. Panel (a): arbitrary small area S on the surface of a radially expanding flow pattern such as that in Figure 19.34(b). Panel (b): enlarged view of area S. Radial velocities at the inner and outer boundaries are V_1 and V_2, respectively. The inner boundary is of length $r\delta\phi$. *Panel (c): the continuous line plots* radial velocity across a diameter of the flow pattern used in the experiment of *Figure 19.34. In the actual experiment*, a black disk occluded the center of the pattern and is represented by the dotted area. The dashed line plots radial velocity for the kind of flow pattern that would be produced by a zooming lens. Panel (d): the continuous line shows the distribution of div V across a diameter of the flow pattern in Figure 19.34(b) and corresponds to the continuous line in (c). The dashed line represents the distribution of div V for the zooming-type flow pattern shown by the dashed line in (c). The experimental data presented in Figure 19.33 indicate that observers are able accurately to locate a local maximum of div V in a flow pattern.

imentally. One kind of hypothesis is framed in terms of local processes. The focus of expansion is a local property of the flow field; the direction of local motion reverses as the observer passes across the focus. Div V is also a local quantity. However, the recent studies described above have suggested that both the focus of expansion and div V are of limited value in guiding self-motion. An alternative to identifying a point in the flow pattern is a form of template matching over some large area of the visual field. A template might be the summed response of many small-field motion detectors, each of which responds best to motion directed radially outward from the focus. In some environments, exploratory eye movements could identify the direction of self-motion, because the summed activity of the motion detectors would be greatest when the eye was gazing directly at the destination, and the flow pattern would then best match the template. However, according to this model, judgments of self-motion would be systematically inaccurate in asymmetric environments, because flow patterns would be markedly asymmetric (Regan, in press).

4. CHANNEL THEORIES OF MOTION IN DEPTH

4.1. Background

One of the most pervasive theoretical concepts in current vision research is that of channels specialized to process different kinds of information. In fact, this same notion stimulated much of the research discussed in this chapter. Although the experimental results may be given other interpretations and have intrinsic value apart from their connection with the channel concept, it is important to be explicit about the theoretical ideas underlying the work that led to the results.

One common proposition is that early processing of visual information is accomplished in part by the activity of sets of parallel channels. Each set of channels is selectively sensitive to an abstract feature of the proximal visual stimulus. Also, each set of channels is presumed to operate independently of other sets, thus "decomposing" the visual input into a number of orthogonal units. The sensitivity of a given set of channels has no substantial overlap with the sensitivity of any other set of channels.

Interactions of the outputs of these hypothetical sets of channels may well occur at later stages of processing of visual information. Such interactions certainly occur among the outputs of individual channels.

It is important to distinguish between a set of channels, for example, the set of color channels, and the individual channels that constitute a set. It may not be possible to define an individual channel as strictly as a "set of channels," because the sensitivities of individual channels may overlap considerably. In addition, the interactions that occur between some individual channels affect their filtering properties. For example, spatial frequency channels may well inhibit each other (Braddick, Campbell, & Atkinson, 1978). The channel theory is discussed in detail elsewhere (Braddick et al., 1978; Graham, 1981; Regan, 1982; Westheimer, 1981). Parallels between the concept of the channel and the old idea of structuralist psychologists who treated sensations as independent elements of consciousness are described by Kaufman (1974, 1979).

Unfortunately, there is some lack of precision in the ways in which the term "channel" has been applied. Sometimes it is used to mean no more than "selective sensitivity." Other authors invoke the uniqueness of some sensation, such as that of "motion" or "pattern" in their usage of the term "channel," looking back to Hering, who inferred the "primacy" of yellow as well as red, green, and blue, partly because of their apparent "purity" (Hurvich & Jameson, 1957). The concept of a "set of channels" does not imply that every or even any unique or simple "sensation" has a corresponding set of channels (Regan, 1982).

Some authors have used the term "channel" to stand for a neural mechanism, a population of neurons, or even some independent structural element, a concept quite similar to the classic doctrine of specific nerve energies. In contrast, "set of channels" is defined here entirely in terms of psychophysics, and anatomical or cellular structures do not enter the definition at all, though interesting and suggestive correlations have indeed been found between channel properties and the properties of neurons and of aggregates of neurons.

4.2. Evidence for Independence of Motion-in-Depth Channels

Figure 19.10(d) shows evidence that the set of changing-size channels responds specifically to the line-of-sight component of a target's motion, and receives no input from the velocity component in the frontal plane; that is, they are "blind" to sideways motion. Contrast was also shown to be irrelevant to the set of changing-size channels, at least insofar as adaptation to changing size may be attributed to such a set of channels. Neither the percentage contrast nor the direction of contrast has any effect on threshold elevations for changing size, provided the stimulus is clearly visible (Petersik et al., 1981; Regan & Beverley, 1978b). Flicker is another attribute of visual stimulation that has no effect on threshold elevations for changing size. Of course, these results do not preclude the possibility that contrast or flicker sensitivity may be mediated by orthogonal channels.

The progenitor of channel theories is the Young-Helmholtz theory of color vision. The balance of activity among three "channels" defines the color sensation associated with any spectral hue or its metameric match. The absence of one such "channel" results in one of three kinds of "color blindness."

Similar specific "blindness" should occur if the channel concept is applicable to changing size and stereo motion, and indeed this is the case. For example, some individuals have a region of the visual field that is "blind" to changing disparity, but sensitive to static binocular disparity, whereas another region is sensitive to changing disparity but "blind" to static disparity. When stimuli are entirely stereoscopic, such individuals can be "blind" to motion in depth while retaining sensitivity to position in depth, and vice versa (Richards & Regan, 1973). A second example is that some patients lose visual sensitivity to intermediate spatial frequencies over a restricted range of orientations while retaining normal sensitivity to both low and high spatial frequencies (Regan, Silver, & Murray, 1977; Regan, Whitlock, Murray, & Beverley, 1980).

4.3. Some Practical Implications of the Channel Concept

Whether or not the channel concept proves to be theoretically sound, it may have heuristic value. Such value has already been displayed, in that the concept has led to many fruitful experimental studies of the visual process. This section considers the ways in which the channel notion may affect investigation in several areas of practical significance.

4.3.1. Transfer of Training. If a complicated skill, such as catching a ball, depends on learned computations carried out on the outputs of a *few sets of channels*, then, once learned, the skills should readily transfer to a wide variety of visual environments. This follows from the independence of the sets of channels from each other, because a given set is supposed to ignore all but one aspect or feature of a visual scene, regardless of the complexity or number of other features. By the same token, if there is considerable overlap or mutual interference among sets of channels in a particular individual, that individual would find it difficult to use learned eye-hand skills in a variety of complex visual environments. Section 5 describes a preliminary test of this prediction in which channel "cross talk" was evaluated in pilots, and this was compared with their performance in a number of flying tasks.

4.3.2. Visual Discrimination. Humans can discriminate among as many as 150 spectral colors even though the three kinds of receptors that mediate color vision are very coarsely tuned. Such observations suggest that stable outputs of coarsely tuned channels may be precisely compared at some secondary stage to mediate a high degree of visual discrimination. There is evidence that this process may take place in other sets of channels as well as the set of color channels. For example, the initial stage of analysis of motion in depth can be modeled by postulating binocular motion channels tuned to four different directions of motion in depth. The most sharply tuned of these channels accepts a range of directions of about 1.5°, as seen in Figure 19.17(b), implying that if a single channel signals the direction of motion in depth, discrimination of differences in direction of motion in depth could not be better than 1.5° (Beverley & Regan, 1973; Regan, Beverley, & Cynader, 1979). However, discrimination is an order of magnitude better, for subjects were able to discriminate among directions of motion in depth that differed by only 0.1–0.2°. [See Figure 19.17(a).] To explain this acute discrimination one might postulate a process in which the outputs *of different channels are compared* with each other. Evidence to support this conjecture includes the fact that discrimination of direction of motion in depth has submaxima along trajectories for which a small change in the direction of motion produces large changes in the balance between different channels. These submaxima are shown in Figure 19.17(a). The vertical dotted lines indicate their close correspondence with the crossover points of the channel sensitivities.

Similar arguments have been used to support a proposed opponent processing of the outputs of channels sensitive to different bands of spatial frequencies (Campbell et al., 1970; Spitzberg & Richards, 1975); and an analogous idea has been advanced to explain "hyperacuity" in orientation sensitivity (Westheimer, Shimamura, & McKee, 1976). Regan and Beverley (1983a, 1984a, 1984c) provide recent empirical evidence to support this notion in the spatial frequency domain and the orientation domain. Clearly this is an area suitable for further research.

4.3.3. Specific Visual Tests for Specific Flying Tasks. If different flying tasks depend on different sets of channels (Regan & Beverley, 1980a), it may be that specific tests of the appropriate sets of channels would predict flying performance in tasks that involve only a few sets of filters. Tests that fail to assess the relevant channels or confound several sets of channels would be less accurately predictive.

4.3.4. Prediction of Performance on Visual Tasks. As noted in Section 2.2.4.4, subtle forms of "blindness" might not be revealed by conventional tests, and would only be revealed behaviorally in tasks that involve the defective channels. Ginsburg, Evans, Sekuler, and Harp (1982) give another example where contrast sensitivity for intermediate spatial frequencies is better than visual acuity in predicting the detection of a target of substantial size. This is discussed in Chapter 34 by Ginsburg.

5. EXPERIMENTAL TESTS OF FLYING PERFORMANCE

Sections 2 and 3 described evidence that the human visual system has rather specific sensitivities to several abstract features of the visual environment including changing size, motion in depth, frontal-plane motion, and the vectors div V and curl V that can occur in the flow pattern produced by self-motion. The idea that different specific sensitivities are important in different flying tasks suggests that visual tests designed to measure individual variations in these specific sensitivities might prove more successful in predicting intersubject differences in flying performance than tests (such as the Snellen test or static stereoacuity test) that fail to test important special sensitivities or tests that confound several special sensitivities in one test result. *It has been suggested that different specific tests might predict performance in different flying tasks* (Regan & Beverley, 1980b).

In light of Gibson's work, an immediate candidate test is one of discriminating different rates of expansion of a flow pattern. Such a test was carried out, using the same stimulus illustrated in Figure 19.34(b), and subjects were required to judge which of two rates of expansion was the faster. Results of this laboratory test were compared with performance in flying tasks in real aircraft and in a flight simulator (Kruk & Regan, 1983; Kruk, Regan, Beverley, & Longridge, 1981, 1983). A second visual test used in these studies was also based on the "specific sensitivity" notion. In this test the subjects viewed a square whose size alternately expanded or contracted at a fixed rate, with the transition between expansion and contraction occurring at unpredictable moments. The subject's task was to turn a knob so as to maintain the square's size constant. This can be regarded as a changing-size or motion-in-depth tracking task as compared with the more conventional task of tracking frontal plane motion (Regan & Beverley, 1980a).

A second kind of visual test was generated by the basic research described above. Section 4 mentioned attempts to determine whether the degree of independence between a pilot's sets of channels affects performance in visually guided flying tasks. It was proposed that a lack of independence between sets of channels that are otherwise adequately sensitive may allow tasks to be carried out satisfactorily in a simple environment, but lead to degraded performance in a complicated visual environment. By the same token, extraordinarily accomplished pilots and athletes may well have highly independent sets of channels. In an attempt to test this hypothesis, groups of pilots with various degrees of experience in aviation were studied (Kruk & Regan, 1983; Kruk et al., 1981, 1983). The tests included many standard tests of visual sensitivity, such as Snellen acuity, contrast threshold, and motion threshold, as well as the expanding flow pattern test and a test designed to assess whether looming sensitivity was independent of frontal-plane motion. As in the tracking task described above, subjects were required to adjust the size of an oscillating test square so as to keep size constant but, in addition to the unpredictable changes in size, the test square was randomly moved in the frontal plane.

Flying tasks were carried out both in a flight simulator and in real aircraft whose locations, velocities, and other parameters were telemetered to a ground station. The simulator was the "Advanced Simulator for Pilot Training" (ASPT) at Williams Air Force Base, Arizona, using a simulated A-10 cockpit. The real aircraft were A-4 and F-14 jet fighters flown by U.S. Navy pilots over the U.S. Marine Corps Air Station Yuma Tactical Air Combat Training System (TACTS) range. Simulator flying tasks included bad visibility landing, formation flight, and a bombing task following a low-level approach under ground threat. Flying tasks in real aircraft included a low-level bombing task and air-to-air combat where success was assessed by the win/loss ratio, that is, the ratio between the number of times the pilot hit an adversary aircraft, and the number of times the pilot was hit by the adversary's missiles. In the low-level task in the simulator, pilots were likely to be shot down by surface-to-air missiles or antiaircraft artillery if they flew above 110 m for more than about 10 sec. The pilot's task was to make a 5000-m approach to the target at a designated altitude of about 36 m (from which altitude the target was not visible), visually judge the correct point to "pop up," pop up to about 760 m and identify the target, then dive and manually release a bomb. Visual factors, particularly judgments of flow patterns, were important for correctly placing the aircraft and hence correctly placing the bomb. The bombing task with real aircraft was similar except there was no ground threat. In both simulator and real aircraft, the low-level task was scored in terms of mean error in bomb impact point relative to the target.

Overall, visual thresholds for contrast sensitivity, motion, and acuity had little or no predictive value with regard to flying performance. Possible reasons include the following. (1) The pilots had nearly equal thresholds. (The Snellen may be too coarse to bring out any difference in acuity that there might be between individual pilots.) (2) The flying tasks largely involved suprathreshold motion and suprathreshold contrast.

The laboratory tests—the flow pattern test and the changing-size tracking test, with and without perturbing frontal-plane motion—did correlate reasonably well with several of the flying tasks. Table 19.2 shows correlations between performance on the flight simulator and visual test results for the flow pattern test, conventional frontal-plane motion tracking, and changing-size tracking with and without frontal-plane "jitter" motion. Subjects were instructor pilots, student pilots, and experienced fighter pilots. The strongest correlations were between flow pattern test results and low-visibility landing performance as measured by the number of crashes ($r = .82$ for the instructor group) and between flow pattern test results and low-level bombing accuracy ($r = .74$). These two correlations point to the importance for low-level maneuvers of accurately judging motion in depth on the basis of flow pattern cues. They emphasize the important role of motion and dynamic visual cues in low-level flight and draw attention to the importance of accurately representing *motion* as well as static spatial factors in flight simulator displays.

Table 19.3 shows correlations between visual test results and low-level bombing accuracy under "no-drop" and "real bomb" conditions. The strongest correlation of .71 was between flow pattern test results and accuracy with real bombs. These results

Table 19.2. Coefficients of Correlation (*r*) Between Simulator Performance and Performance on Visual Tests

	Fighter Pilots		Instructors		Student Pilots	
Simulator Task	*r*	*p*	*r*	*p*	*r*	*p*
Landing—correction to runway	Frontal-plane tracking −.65	.01	Frontal-plane tracking −.61	.03	Frontal-plane tracking −.66	.009
Landing—crashes on runway	Changing-size tracking .63	.02	Flow pattern test −.82	.01		
Formation flight—time in position for fingertip task	Flow pattern test .61	.03	—		Flow pattern ($n = 6$) .52	.15
					Perturbed changing-size tracking −.56	.03
Formation flight—time in position for trail task	—		Flow pattern test .55	.05	—	
			Changing-size tracking −.57	.03		
Bombing—hits on target	Flow pattern test .74	.008	—		—	

All correlations not included are of significance lower than .05. Visual tasks were flow pattern velocity discrimination, conventional frontal-plane motion tracking, changing-size tracking, and perturbed changing-size tracking (random frontal-plane motion added). Simulator flight tests included low-visibility landing, formation flying, and a bombing task with low-level approach under ground threat. (See text for fuller description.) Subjects were 12 instructor pilots and 12 student pilots from Williams Air Force Base and 12 experienced fighter pilots. Strong correlations of flow pattern test results with crashes during landing (instructor group) and with bombing accuracy (fighter pilot group) suggest the importance of suprathreshold motion discrimination and flow pattern cues for low-level flying. (From R. Kruk, D. Regan, K. I. Beverley, & T. Longridge, Flying performance on the Advanced Simulator for Pilot Training and laboratory tests of vision, *Human Factors*, 1983, 25. Copyright 1983 by The Human Factors Society. Reprinted with permission.)

with real aircraft parallel the simulator findings. The low-level task was designed with the aim that guidance should strongly depend on visual cues, and on the assumption that guidance of the aircraft would be reflected in bombing accuracy. The correlations shown in Table 19.3 suggest that the visual abilities measured by discrimination of *rate of change in expanding flow* patterns and the ability to use changing-size stimulation in an eye-hand coordination task are important for accurate guidance in low-level flight. Furthermore, individual differences between these abilities correlate with individual differences in flying performance on this task. Section 3.2 provides evidence that specific sensitivity to changing size or looming may be common to both the tracking task and the flow pattern task.

Table 19.3. Coefficients of Correlation (*r*) Between Visual Test Results and Performance in Low-Level Flying Tasks

Correlation	*r*	*p*
Between no-drop bombing accuracy and		
Flow pattern velocity discrimination	.67	.01
Perturbed changing-size tracking	.63	.02
Frontal-plane motion tracking	.52	.05
Between bombing accuracy (real bombs) and		
Flow pattern velocity discrimination	.71	.01
Perturbed changing-size tracking	.57	.04
Between no-drop bombing accuracy and bombing accuracy (real bombs)	.73	.01

Flight tests included accuracy of computer-scored "no-drop" bombing in the telemetered TACTS range at Yuma and bombing accuracy using real bombs. Subjects were 12 experienced fighter pilots who flew A-4 aircraft. (See text for fuller description of flying tasks and visual tests.) Results suggest that the flow pattern test and changing-size tracking measure visual abilities that are important to good performance on low-level flight tasks. (From R. Kruk & D. Regan, Visual test results compared with flying performance in telemetry-tracked aircraft, *Aviation, Space, and Environmental Medicine*, 1983, *54*. Reprinted with permission.)

In addition to laboratory tests and flying performance tasks, pilots were also required to carry out an airborne visual test (Kruk & Regan, 1983). In this test two A-4 aircraft were vectored toward each other from a range of about 40 km. One aircraft was designated as the target and the other as the attacker. The attacker gave a signal as soon as the target aircraft was detected. This "visual acquisition distance" was 5,500–10,600 m (mean 8,600 m) for nonsmoking aircraft. On hearing the attacker pilot's signal, the target aircraft immediately banked and turned sharply left or right. As soon as the attacker was able to judge the direction of turn, the attacker signaled leftward or rightward. Kruk and Regan (1983) measured the attacker's ability to detect the direction of turn in two ways—first, as the angular displacement of the target aircraft between the start of the target's turn and the attacker's correct signal and, second, as the distance between aircraft at the instant that this second signal was made. The rationale for these tests was that an advantage in air-to-air combat is held by the pilot who (1) sees his adversary before being seen, and/or (2) after combat is joined, responds early and correctly to a change in the adversary's heading.

Table 19.4 gives correlations between the results of both laboratory and airborne visual tests and measures of combat performance. Note that in Table 19.4 aircraft are divided into those whose engines smoked and those with nonsmoking engines. The correlations mentioned in the text are for aircraft that left no visible smoke trail. Success in combat, as measured by the win/loss ratio, correlated most strongly with the airborne visual test results (r = .74 for acquisition range, .79 for direction detection range, and .85 for angular deflection). Laboratory tests were comparatively unsuccessful in predicting performance, apart from the two changing-size tracking tests, which gave fair correlations with the number of missile shots fired per engagement. This latter finding seems reasonable because visual-motor tracking skills are involved in the ability to hold an aircraft in one's missile sights while the adversary maneuvers in an attempt to escape from a vulnerable position.

Among the visual cues that might have enabled the attacker pilot to discriminate between the target's leftward and rightward turns are (1) leftward or rightward frontal plane motion, and (2) the aspect or silhouette shape of the aircraft. Aspect might be important because, when turning, the target aircraft first briefly assumed the appropriate angle of bank (in less than 1 sec), and then altered heading. The aspect of the aircraft was quite different for the two angles of bank so that, as discussed by Kennedy et al. (1982), aspect provided a visual cue to heading. The two cues of aspect and frontal-plane motion could not be dissociated in the air, so Kruk and Regan (1983) carried out a subsidiary study using a model aircraft. Subjects were required to discriminate between the two angles of bank for the model aircraft at different viewing distances. Discriminations between left and right bank could be made from a distance at which the aircraft subtended only 3–4 min arc. One difficulty in comparing the detection and discrimination distances obtained in the laboratory using the model A-4 airplane with the distances obtained in the airborne visual tests using real A-4 aircraft is how to allow for the different atmospheric conditions and lighting levels. To deal with this problem, the two sets of data were normalized relative to visual acquisition distance. Kruk and Regan concluded that aspect alone could account for subjects' ability to judge direction of turn correctly at ranges of 1,700–8,800 m (mean 5,300 m) with real A-4 aircraft. On the other hand, this does not mean that the cue of frontal-plane motion was not used.

The finding that flying performance correlates with the expanding flow pattern test results is consistent with the Gibsonian notion that information in the changing optic array can be used by the pilot. On the basis of research described in Section 3, we can add a suggestion that the information in the optic array actually used by the pilots may have included the location of the maximum div **V** as well as the location of the focus of the velocity flow pattern, noting that the flow pattern actually used had a sharp maximum of div **V** at the *focus of expansion*.

6. SUMMARY

The idea that the visual system has a specific response to dynamically changing size is supported by the finding that changing-size sensitivity is specifically reduced by adapting to chang-

Table 19.4. Coefficients of Correlation (*r*) Between Laboratory and Airborne Visual Test Results and Performance in Simulated Air-to-Air Combat Using Real Aircraft

	Nonsmoking Aircraft ($N = 6$)		Smoking Aircraft ($N = 8$)	
	r	*p*	*r*	*p*
Correlation between acquisition range and				
Kills/engagement	.80	.03	.69	.01
Died/engagement	−.85	.02	NS	—
Win/loss ratio	.74	.05	NS	—
Direction detect range	.79	.03	.96	.001
Flow pattern velocity discrimination	−.60	.10	−.61	.02
Correlation between detection range and				
Died/shot at	−.77	.04	NS	—
Died/engagement	−.88	.01	NS	—
Win/loss ratio	.79	.03	NS	—
Kills/shot	NS	—	.65	.04
Angular deflection	−.91	.006	NS	—
Correlation between angular deflection and				
Shots/engagement	−.83	.02	NS	—
Shot at/engagement	.78	.03	.77	.01
Died/engagement	.69	.06	.79	.009
Win/loss ratio	−.85	.02	NS	.08
Frontal-plane motion tracking	NS	—	−.71	.02
Changing-size tracking	.80	.03	NS	—
Flow pattern velocity discrimination	NS	—	−.66	.04
		All Aircraft		
		p	*r*	
Correlation between shots/engagement and				
Changing-size tracking		−.67	.01	
Perturbed changing-size tracking		−.67	.01	

Correlations not reported were not statistically significant (NS). Subjects were 11 experienced fighter pilots. Airborne visual tests were conducted with subject (designated as attacker) engaged in maneuvers with a second aircraft (designated as target). Tests included (1) acquisition range—distance at which attacker first sighted target aircraft; (2) direction detection range—distance between attacking and target aircraft at time attacker first discriminated direction of an escape turn executed by target immediately upon detection by attacker; (3) angular deflection—angular displacement of target aircraft between beginning of escape turn and attacker's detection of direction of turn. Combat performance was measured during routine air combat training missions. Data collected included number of missiles fired, number of hits, times shot, and number of times shot down. (See text for more detailed description of both airborne and laboratory visual tests.) It was necessary to analyze individual aircraft whose engines emitted visible smoke separately from nonsmoking aircraft. For nonsmoking aircraft, visual acquisition difference ranged from 5,500 to 10,600 m and left/right discrimination distances ranged from 1,700 to 8,800 m. Airborne visual test results were more successful than laboratory visual tests in predicting pilots' performance during air-to-air combat. (From R. Kruk & D. Regan, Visual test results compared with flying performance in telemetry-tracked aircraft, *Aviation, Space, and Environmental Medicine*, 1983, *54*. Reprinted with permission.)

ing size and that this effect cannot be explained in terms of sensitivity to frontal plane motion. A changing-size stimulus can produce a sensation of motion in depth as well as a sensation of changing size, but these effects have different properties. Size oscillations can be perceived as such up to at least 10 Hz, but the associated sensations of motion in depth fail above about 3 Hz.

The human visual pathway seems to contain at least two stereoscopic systems, one for position in depth and the other for motion in depth. The first is the classic disparity-sensitive system for relative position in depth. The second involves sensitivity to the relative velocities of the left and right retinal images (V_L/V_R), and mediates the precise 0.1–0.2° stereoscopic judgments of the direction of motion in depth. The stereo motion system involves four pairs of channels, tuned to different values of the ratio V_L/V_R.

The sensation of motion in depth can be elicited both stereoscopically (by changing disparity) and monocularly (by changing size). Motion in depth is a unitary sensation in that it can be canceled to zero by pitting changing size against changing disparity. The relative effectiveness of the stereoscopic and monocular stimuli depend on object speed, width, and inspection time, but not on object distance.

The visual guidance of self-motion is understood in general terms, but the specific information processing and visual computations that underlie visual guidance are not known. When the magnification of a patterned target is increased so that the rate of change of magnification is uniform over its entire area, contours flow radially away from a focus where local velocity changes sign. This focus is a candidate cue for visual guidance, and subjects can locate this focus when no translational motion is impressed on the pattern. *However, when the retinal image* of the whole pattern translates across the retina as well as expanding, *subjects can no longer locate the focus with precision*, and this raises a problem for the general validity of this local cue. Subjects can locate a local maximum in the rate of expansion even when the pattern is translating, but the destination of self-motion often does not coincide with such a local maximum. Rather than explaining visual guidance in terms of sensitivity to local properties, a wide-field template-matching process could be suggested, but there is little pertinent experimental evidence.

Attempts have been made to correlate flying performance with the results of psychophysical tests of vision. Thresholds did not predict performance in other than detection tasks. For more complex flying tasks such as low-level flying performance and air-to-air combat, closer correlations were obtained with suprathreshold test results using an expanding flow pattern and motion-in-depth tracking.

APPENDIX: CALCULATION OF DIV V FOR A UNIDIRECTIONALLY EXPANDING PATTERN AND FOR A RADIALLY EXPANDING PATTERN

First we consider the unidirectionally expanding pattern as Figure 19.32. The dots outline an arbitrary small area S; x and y are Cartesian coordinates on the pattern. In the special case of a two-dimensional surface, such as that shown in Figure 19.32, we have

$$\operatorname{div} \mathbf{V} = \lim_{S \to 0} \frac{\oint \mathbf{V} \cdot d\mathbf{l}}{S}$$

where S is a small area and $\mathbf{V} \cdot \mathbf{dl}$ is the product of an element along the boundary of area S and the component of $\mathbf{V}$ perpendicular to the boundary. In Figure 19.32,

$$\operatorname{div} \mathbf{V} = \frac{1}{S}(V_2\Delta y - V_1\Delta y) = \frac{\partial V}{\partial x}$$

where $\partial V/\partial x$ is the local rate of change of velocity with respect to distance across the pattern. Hence, in Experiment 1, div $\mathbf{V}$ was uniform across the pattern, because for $n = 1$, in Figure 19.33(a) the plot is a straight line so the magnitude of *div* $\mathbf{V} = \partial V/\partial x$ *is the same at all points.* On the other hand, in Experiment 3, with exponent $n = 0.5$, for example, the slope $(\partial V/\partial x)$ of the plot in Figure 19.33(a) is steeper at the center of the pattern than to either side; hence div $\mathbf{V}$ is larger at the center because the magnitude of div $\mathbf{V}$ is equal to $\partial V/\partial x$. Note that div $\mathbf{V}$ is formally defined in terms of the limiting case when area S becomes vanishingly small, but that any practical physiological mechanism would have a finite receptive field area, and so would be only a rough approximation to a div $\mathbf{V}$ detector.

Now we turn to the radially expanding pattern used in the experiment of Figure 19.34(b). The flow pattern is illustrated in Figure 19.35(a). *First we calculate the area S of the* small region outlined by the continuous line. The difference between the areas of the larger and smaller dotted circles is $\pi(r + \Delta r)^2 - \pi r^2$. Hence, approximately

$$S = \frac{\Delta\theta}{2\pi}(2\pi r\Delta r) = r\Delta r\Delta\theta\,. \tag{1}$$

Div $\mathbf{V}$ is related to the stimulus parameters as follows:

In the two-dimensional case

$$\operatorname{div} \mathbf{V} = \lim_{S \to 0} \frac{\oint \mathbf{V} \cdot \boldsymbol{dl}}{S}\,.$$

Therefore,

$$\operatorname{div} \mathbf{V} = \lim_{S \to 0} \frac{[V_2(r + \Delta r)\Delta\theta - V_1 r\Delta\theta]}{S}\,. \tag{2}$$

Substituting in Eq. (2) from Eq. (1)

$$\operatorname{div} \mathbf{V} = \frac{\partial V}{\partial r} + \frac{V}{r} \tag{3}$$

where V is the velocity at any point P on the surface and $\partial V/\partial r$ is the rate of change of velocity with respect to radial distance at point P. The continuous line in Figure 19.35(c) shows the radial distribution of velocity for the flow pattern used in the experiment of Figure 19.34. The distribution of div $\mathbf{V}$ over the surface can be calculated for Eq. (3), and is plotted as a continuous line in Figure 19.35(d). Div $\mathbf{V}$ was not uniform over the surface, but rather had a sharp maximum near the center.

For completeness we note the special case that velocity is directly proportional to radial distance. This special case [broken line in Fig. 19.35(c)] corresponds to the effect of a zoom lens; the rate of increase of magnification is the same over the whole scene. Because V is proportional to r, $\partial V/\partial r$ is uniform over the whole surface, so that at any point $V = \partial V/\partial r$. Equation (3) reduces to div $\mathbf{V} = 2(\partial V/\partial r)$, that is, div $\mathbf{V}$ is uniform over the whole surface. For comparison, div $\mathbf{V}$ for this special case is plotted as a broken line in Figure 19.35(d).

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SECTION 3

The Higher Derivatives and Perception

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A. Suprathreshold Experiment

The experiments described in Section 1 of this report do not distinguish between effects of acceleration and effects of jerk on the judgment of the subject as to whether or not the motion was smooth (uniform). The reason for this is illustrated in Figure 1 of this section. The figure shows that where the modulation of speed is sinusoidal, the stimulus contains an average speed (first derivative), acceleration (second derivative) and jerk (third derivative). Where the first derivativate is sinusoidal, the second derivative is a cosine wave, and the third derivative varies over time as a negative sine wave of the same frequency. In this experiment we set out to discover if a subject is capable of separately responding to the latter two terms.

A grating was made to drift across a CRT from left to right at an average speed of 5 deg/sec, and its speed was modulated at a frequency of 2 Hz. The modulation of speed was about 70%, and it was visible to all observers. A second CRT display was placed next to the one used to present the moving grating. A simple spot of light was moved vertically up and down on the CRT at the frequency used to modulate the speed of the grating. The subject was given control over the phase angle of the sinusoidally moving spot. (The latter was accomplished by applying the signal used to modulate the speed of the grating to a PAR JB6 lock-in amplifier which contains a phase shifting circuit. The subject simply turned a knob on the lock-in to shift the phase of the signal at the appropriate output on the lock-in.) The subject was instructed to shift the phase of the signal moving the spot along the Y axis of the oscilloscope so that it was in-step with the speed change, i.e., at its highest point when speed was maximum and at its lowest point when speed was at its minimum. In an independent session the subject was instructed to place the spot at the top of its excursion when the grating was changing speed at its fastest rate, and at its lowermost point when the change of speed was slowest. The first set of instructions was designed to show that the subject is sensitive to speed per se, while the second set was designed to show that the subject is sensitive to acceleration too. A positive finding with regard to sensitivity to acceleration would be indicated by a phase difference of 90 deg between the results obtained under the first and second sets of instructions.

Thus far we have only preliminary results. These indicate that it is possible for a subject to respond to the acceleration of the grating. In a modification of this procedure, one that was designed to determine if a subject can respond to jerk as well as acceleration, we obtained negative results. In any event, we deferred further work on this experiment until recently, and we shall have to run several more subjects before making a definitive conclusion. This work is being done on an extension to the program described in this report.

B. Adaptation to the Higher Derivatives

The foregoing experiment, even when completed, is incapable of settling the issue of whether the detection of acceleration is more a matter of judgment or of perception. One subject reported that he felt as though he was first finding the point in time when things were speeding up very rapidly, and then another point in time when things were slowing down very rapidly. Even this type of description could confound judgmental and perceptual factors. To directly attack this issue we used an adaptation paradigm.

As is well known, the results of adaptation experiments are often used to determine if different stimuli are affecting overlapping or orthogonal "channels" or "sets of channels" (see the discussion of these terms in Section 2 of this report). If adaptation to one stimulus has no effect on sensitivity to another stimulus, then it is assumed that the two stimuli are affecting different mechanisms within the nervous system (the superposition principle applies). Alternatively, if adaptation to one stimulus affects sensitivty to another stimulus, then it is assumed that a common mechanism is involved.

Another typical use of the adaptation paradigm is that of examining the effects of viewing a critical stimulus on the appearance of some other stimulus, without measuring sensitivity to one or the other. One example of this procedure is the so-called waterfall illusion in which a stationary pattern appears to move after viewing a moving pattern for some time. Moreoer, the direction of motion is opposed to the direction of motion of the moving adaptation pattern. Such evidence was invoked to suport the hypothesis of the presence of polarized motion detectors in the human visual system.

Thus far we have completed some simple observations using the second type of adaptation paradigm. Using stimuli such as those generated during the experiments described in Section 1, subjects stared at a grating of a particular spatial frequency, average velocity, and 80% depth of modulation of speed. The frequency of changing speed was varied from trial to trial but was usually 2 or 4 Hz. After fixating a point on the screen for 10 min, during which time the parameters of the display were held constant, the subject viewed either a stationary pattern of the same spatial frequency, or a similar pattern that moved either in the direction of motion of the adaptation pattern or in the opposite direction (we have not yet tried orthogonal directions of motion in the test display). We were testing the hypothesis that mechanisms tuned to respond to acceleration (or jerk) can be selectively fatigued during adaptation, and therefore a uniformly moving display (or a stationary display) would be seen as moving non-uniformly. We failed to confirm this hypothesis. In point of fact, the stationary display did appear to move, but its motion was opposite to the direction of motion of the non-uniformly moving adaptation display, and the motion after effect was smooth. In short, we obtained a waterfall illusion that was not discernalby different from what can be obtained using a uniformly moving grating for adaptation purposes. This result is consistent with the view that separate detectors of acceleration in the frontal plane do not exist in the human visual system.

Our attempts to conduct studies similar to those described in the first type of use of adaptation were retarded by this finding. It simply did not appear to be a good experimental bet to go to great pains to obtain essentially negative results. Hence, the use of adaptation and the determination of its effect on psychophysically measured sensitivity was put off indefinitely.

C. Square Wave Modulation vs. Triangular Wave Modulation

As illustrated in Figure 1, sinusoidal modulation of the speed of a drifting grating generates both acceleration and jerk. These second and third deriviatives are both finite and sinusoidal in form. Square wave modulation of speed of a grating (Figure 2) causes the speed of a grating to abruptly switch from one constant value to another. The second and third derivatives are portrayed in Figure 2 as impulses, which connote the fact that the higher derivatives are infinite. The average speed of the two constant speeds is physically absent in this type of modulation, whereas the average speed is physically present with sinusoidal modulation of speed. Even so, a grating whose speed is modulated by a square wave can appear to move smoothly when the modulation frequency is sufficiently high, as in apparent motion.

Still another type of modulation is provided by a triangular wave, as shown in Figure 3. It is important to note that this modulation signal has a finite and uniform acceleration term and an infinite third derivative. Thus, the third derivative of type of modulation is identical to that of square wave modulation, but the second order terms of the two waveforms are different.

Periodic square and triangular waves of the same fundamental frequency differ in Fourier composition, i.e., the amplitudes and phases of their Fourier components differ although all of the higher components are odd harmonics of the same fundamental frequency. In fact, the differences between the higher harmonics account for the differences between their higher dirivatives. Therefore, it is possible to determine if a person can sense the higher derivatives by asking him or her to identify which of two sequentially presented stimuli is the one that is square wave modulated, and which is modulated by a triangular wave. We hypothesized that a sophisticated subject would be able to discriminate between a triangular wave and a square wave over a range of modulation frequencies and depths of modulation. This discrimination could be based on the differences between the second derivatives of the patterns. Moreover, variation in the response with frequency (or the temporal period of the modulation) should be indicative of the length of time needed for sensing or detecting acceleration.

Thus far we have completed the programming needed to conduct this experiment, and appropriate display and display generator are in-place. We shall complete data collection shortly.

D. Ramp Modulation vs. Triangular Wave Modulation

Figure 4 shows how speed may be modulated by a periodic ramp (sawtooth) function of time. This type of modulation is accompanied by uniform acceleration and infinite third derivative. However, the third derivative is unidirectional whereas that associated with triangular modulation is of alternating orientation (Figure 3) and at twice the frequency of the third derivative of the ramp frequency.

In our experiments the subjects adjust the fundamental frequency of the ramp until it seems to match that of the triangular wave. If the subject is insensitive to the direction of jerk, the chosen ramp frequency would be twice that of the triangular modulating function. Our results to date are consistent with this hypothesis. A detailed report will follow completion of the experiment.

E. Random Dot Experiments

During the last year of the effort being described in this report, we initiated theoretical work and the development of software and hardware needed for a related set of experiments. This work led to our receiving an additional year of funding from AFOSR, and the work supported by that funding is still underway.

One of the problems we considered late in the program being described here was that of the role of contours or edges in motion perception. It is now established that the motion sensitive neurons of visual cortex are also orientation specific. These neurons tend to respond best to moving lines or edges, where the motion is orthgonal to the direction of the edge or line. However, at least in macaque, motion sensitive neurons of medial temporal cortex are responsive to motion per se, and are "indifferent" to the orientations of the moving stimulus patterns. This led us to consider using dynamic random dot patterns as stimuli to study the perception of the higher derivatives of motion.

A further consideration is related to the fact that we were interested not only in the effects of changes in speed or of acceleration in one direction, but also in the effect of changes in direction of motion on perception. A target moving around a circular path, for example, is accelerating, even if its instantaneous speed is not changing. This type of motion is easily perceived as being circular (or along a curved path in the more general case of non-linear motion). Hence, it would be incorrect to conclude that the visual system is insensitive to acceleration solely on the basis of studies of motion along linear paths in the frontal plane. Again, dynamic random dots seemed to provide the best means for studying changes in direction of motion without confounding the experiment by introducing contours that change orientation over time.

To accomplish this we started construction on a pseudo-random number generator which would be incorporated in our LSI 11/23 computer. The device operates at many times the speed of equivalent software. Its output is an 8 MHz series of 16-bit pseudo-random numbers. These are cycled into a buffer area accessed by the display portion of our program, resulting in a continually changing pattern of randomly selected dots in motion against a dynamic noise background. This program was being linked to a program that would permit the actual collection of psychophysical data during the succeeding year. The board itself was to be delivered shortly after the onset of this new effort.

F. Additional Improvements to Apparatus

As indicated in the Interim Report covering 1983, we developed a rather elaborate program to allow us to generate displays of moving grating patterns and collect psychophysical data. This program (known as "csick") was limited in its ability to produce a wide range of stimuli. Also, it lacked flexibility in that we could not do pilot experiments involving method of adjustment, for example.

To remedy these difficulties we purchased a Picasso Innisfree image generator using funds from this project. It allowed us to overcome the difficulties associated with getting high-quality software to generate a wide variety of displays. This addition to our laboratory was an excellent choice, as we have been able to use the image gnerator in a large number of different experiments - even some that are unrelated to this particular project. This. of course, is in addition to the standard instrument (HP function generators, X-Y oscilloscopes, and so on) that were needed to impelement this project.

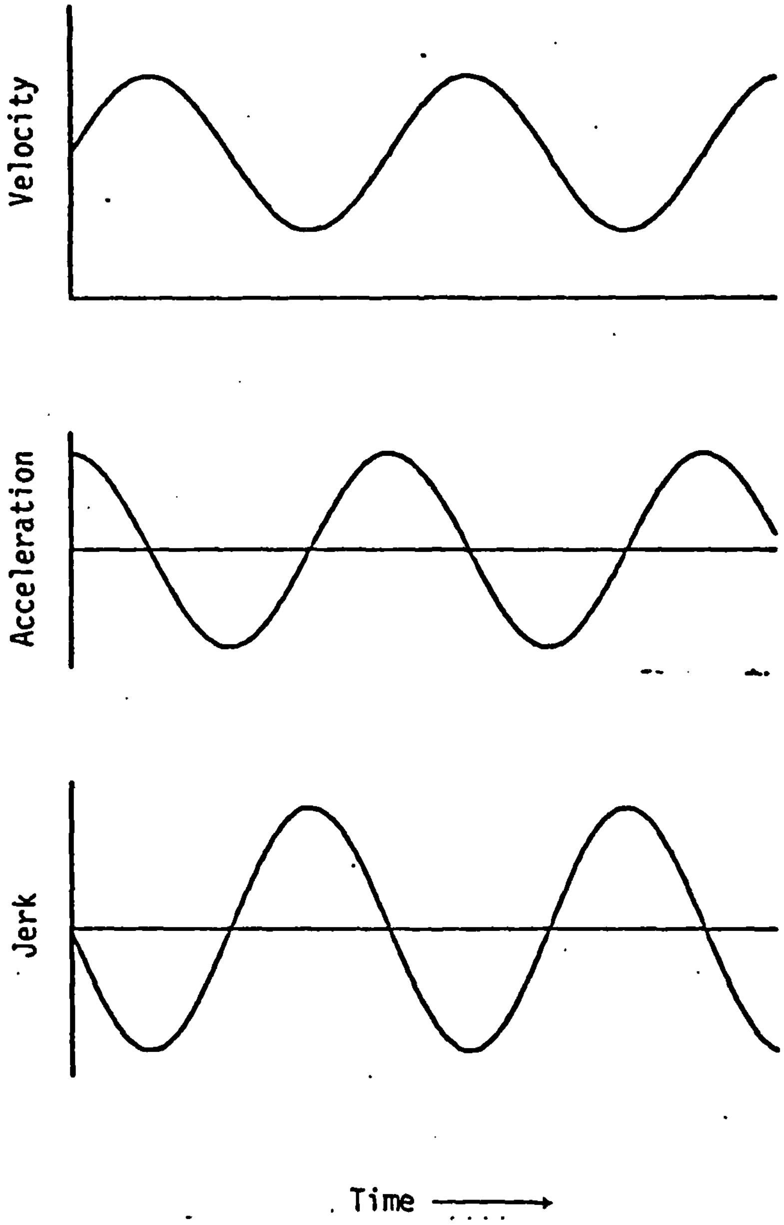

Figure 1 (see text)

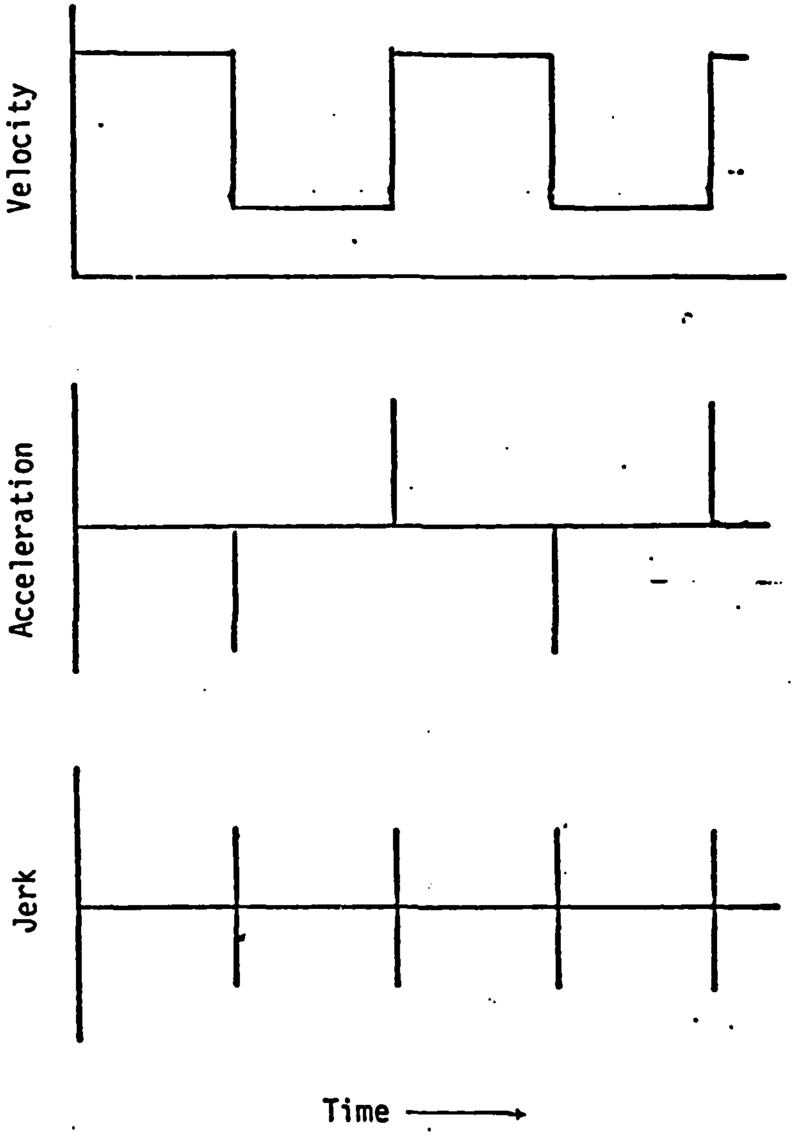

Figure 2 (see text)

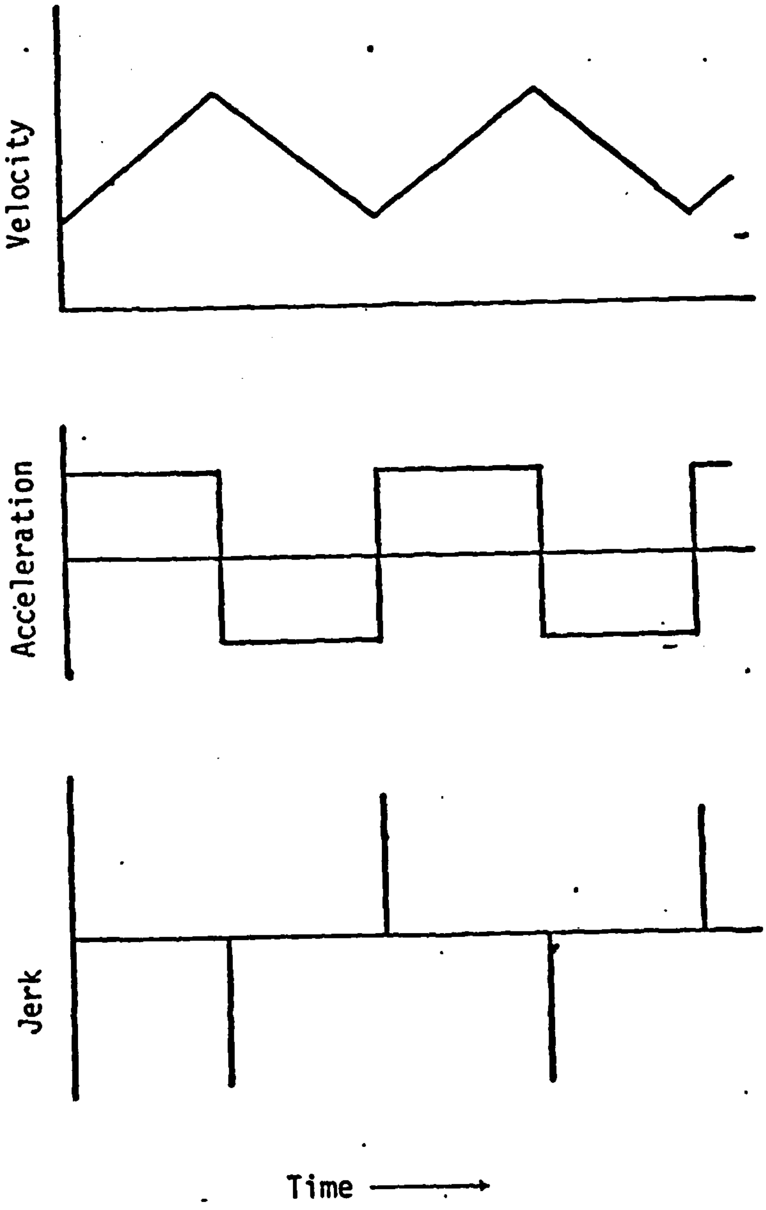

Figure 3 (see text)

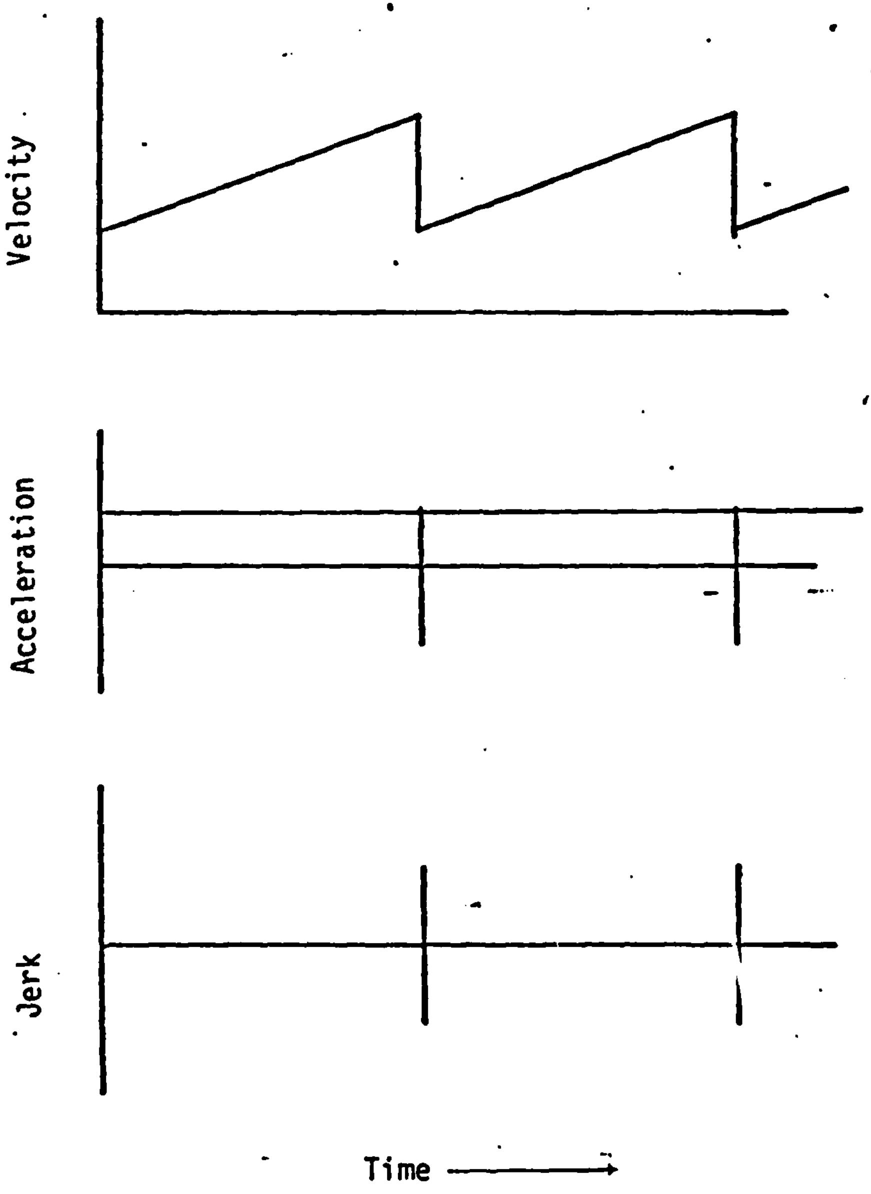

Figure 4 (see text)

SECTION 4

Personnel

The following personnel were assigned to this task at one stage or another during its execution:

Lloyd Kaufman, Principal Investigator

Samuel J. Williamson, Co-PI

Reid Tannenbaum, Research Assistant

David Dorfman, Research Assistant

Aries Arditi, Consultant (author of csick)

J. Anthony Movshon, Unpaid Consultant

Andrea Sulzer, Work-study Student

R. Picardi, Engineer

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