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The Role of Exocentric Reference Frames in the Perception of Visual Direction

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One classic piece of evidence for an efference copy signal of eye position is that a small, positive afterimage viewed in darkness is perceived to move with the eye. When a small stationary reference point is visible the afterimage appears to move relative to the reference point. However, this is true only when the afterimage is localized to a small area. We have observed that when an extended afterimage of a complex scene is generated by a brief, bright flash it does not appear to move, even with large changes in eye position. When subjects were instructed to maintain their direction of gaze, we observed small saccades (typically < 1 deg) and slow drift movements often totalling more than 10 deg over a 30 sec period. When the instructions were to simply inspect the extended afterimage, subjects made larger saccades (up to 5 deg) which were not accompanied by afterimage movement. The smaller movements observed under the first instructions are greater than those observed in the dark or with small afterimages. When a visible reference is present with these large afterimages, the afterimage appears stationary, while the reference point appears to move. Eye position was monitored following the generation of such afterimages. In general, the perceived motion of the stationary reference point was in a direction opposite to the motion of the eye. Similar drift movements of smaller magnitude were observed with localized afterimages, but the motion was attributed to the afterimage. This suggests that with whole scene afterimages, extraretinal information about slow movements and small to moderate saccades is absent or suppressed, and that stationarity is assigned to the complex scene. This indicates a perceptual disposition to rely on visual information (when it is available) for maintaining constancy of visual direction, despite substantial changes in eye position. We found that changes in gaze as large as 13 deg produced no change in reported position of the large scene afterimage. When a small, stationary reference light was present it appeared to move in the afterimage scene in a way consistent with the recorded eye movements. When observers attempted to maintain their direction of gaze, most of the eye movements were slow drift, with occasional small saccades. When the instruction to hold gaze was relaxed, larger saccades up to about 5 deg were observed which were not accompanied by afterimage movement.

Reference frames   Visual direction constancy   Eye movements   Afterimages

Vision operates in the presence of continual displacements of the retinal image as a consequence of eye, head, and body movements. Despite these movements, the visual system is able to maintain excellent localization of objects with respect to the body. This is usually referred to as "visual direction constancy", and is manifest not only in the constancy of directional judgments either of the eye or by pointing with the hand, but also by the absence of a percept of change in the position of objects in the scene, i.e. visual stability. In the case of eye movements, this ability is commonly attributed to a mechanism which uses an extraretinal eye position signal to perceptually compensate for changes in the position of the eye. This is usually assumed to involve some kind of algebraic summation of visual and eye position signals (Matin, 1986). There is manifold evidence that an eye position signal is used together with retinal image location to compute head-centered location. Most directly, judgments of location of a point in the dark with respect to the head can be made with an accuracy of a few degrees, independently of the position of the eye (Matin, 1986). Similarly, a small, positive afterimage viewed in the dark appears to move with the eye (Mack & Bachant, 1969). In this case, the location of the afterimage is determined entirely by the eye position signal, since the image is fixed on the retina. Indeed the perceived location of the afterimage has been used to infer the dynamics of this signal (Grüsser, Krizic & Weiss, 1987).

Although many phenomena reveal the use of an eye position signal in reduced visual contexts, it is also possible that in normal visual environments, perceived stability and constancy of directional judgments are achieved by using a reference frame external to the body.

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Many regularities exist in the stream of incoming visual information which can serve as a basis for use of an external reference frame. For example, the relative positions of objects in a scene are preserved during congruent eye movements, and many horizontal and vertical structures in the field can serve as anchors (e.g. Gibson, 1966; Newell, Rosenbloom & Laird, 1989). Clear evidence for such effects of the visual context on location judgments has been demonstrated by Matin, Picoult, Stevens, Edwards, Yung and MacArthur (1982) and by Stark and Bridgeman (1983). An incorrect efferent signal about eye position, resulting from partial paralysis of the extra-ocular muscles or by ocular displacement, is found to bias judgments of visual direction in the dark, but not in a normal structured environment. (Bridgeman has called these context effects "visual capture of Matin".) The implication of these results is that the eye position signal is given less weight when there is a visual scene present, at least for judgments of straight ahead.

In this paper we provide evidence of a different kind for the role of the visual context in judgments of visual direction. We make use of a striking afterimage phenomenon which has been observed informally by a number of investigators and reported by Swindle (1916), and later by Davies (1973). If a darkened room is briefly illuminated by a bright flash, observers report extraordinarily realistic afterimages which appear to have all the normal surface structure and depth of ordinary viewing. These afterimages appear with a latency of a second or two, and may last as long as a minute or so before decaying to a blotchy residue more commonly experienced with afterimages. In this situation we have available a relatively normal visual context without changes in retinal image position normally consequent on eye movements. We made use of this decoupling of retinal image and eye position information to investigate the role of visual context in egocentric location. We have observed, in striking contrast to the case of small afterimages, that these large-scene afterimages do not appear to move with the eye but instead maintain a constant position with respect to the observer. In addition, the presence of these large afterimages makes it more difficult for subjects to maintain a constant gaze position. Further, when a small stationary light is present in the visual field, retinal image motion resulting from eye movements is attributed to movement of the light itself and the afterimage appears stationary. This latter observation has also been reported by Power (1983). This suggests that with whole scene afterimages extraretinal information is given less weight than with small isolated patches in the dark, and that there is a perceptual disposition to see the visual world as stationary despite large changes in eye position.

To explore this phenomenon we monitored changes in eye position following the generation of these large-scene afterimages, and compared them with similar measurements made for small, circular afterimages. The afterimages were viewed either in darkness or in the presence of a small, stationary light. In addition, observers made perceptual judgments about changes in apparent position of the afterimage and of the stationary light.

METHOD

Eye movement recording

Subjects' right eye positions were monitored with a Dual-Purkinje Image eye-tracker controlled by a Macintosh II computer. Each subject was fitted with a bite bar of dental impression compound to stabilize the head during calibration and data collection. The left eye was covered with an eye patch. The laboratory computer recorded horizontal and vertical eye position as a function of time, as well as a "blink" channel that indicated loss of track, or blinks by the subject. The eye position signal was sampled at either 20 or 250 Hz for a more fine grained analysis of the records. In addition, the eye position files were checked for evidence of a "false lock", in which the tracker incorrectly locks on to the iris instead of the first Purkinje image. Such false locks were a problem during the experiment because of the rapid constriction of the pupil when the strobes were fired to produce the large afterimages. The infrared measuring bean on the eye tracker was attenuated so as to be invisible to the subject in the conditions of the experiment, in order to eliminate a visible reference point.

Procedure

Subjects' eye positions were monitored under five conditions: (1) with an extended positive afterimage of the laboratory scene; (2) with the extended positive afterimage and a visible reference spot; (3) with a small (20 arc min), positive afterimage centered on the fovea; (4) in the dark; and (5) with only a visible reference spot. In all conditions subjects were instructed to attempt to maintain their direction of gaze (left/right and at eye level) for a 30 sec period. In the three afterimage conditions, they were instructed to close their eyes if the afterimage became unclear before the 30 sec maximum trial duration. Figure 1 shows the scene illuminated by the flash. A "bullseye" target, shown in the figure, was placed 1 m from the subject. The center of the target was dimly illuminated with a red LED to allow the subject to fixate the center at the beginning of each trial. For the *extended afterimage* conditions, two electronic flash units [Vivitar model 283 (GN 110) and Sunpak model 622 (GN 160) delivering 2500 $\mathrm{lm \cdot sec \cdot m^{-2}}$ in 20 msec to the bullseye target], were used; the first to provide wide field illumination, the second for extra illumination of the bullseye target. The extended afterimages in these conditions typically included a portion of the desktop, the bullseye target, a book placed upright near the target, and patterned fabric on the wall 0.7 m behind the target. Fiducial marks on the bullseye target were used for calibration before each block of trials. While the entire room was visible during the brief flash, a strong, positive afterimage was created that subtended approx. 45 deg. In the *extended afterimage* condition, the LED was turned off as the electronic flash units were fired. In the *extended afterimage with visible reference* condition, the LED in the center of the target was left illuminated throughout the trial. In the *small afterimage* condition, a single flash unit was placed behind the target, back-illuminating a 20 arc min diffuser in the center of the bullseye target.

Subjects were instructed to attempt to maintain their direction of gaze as long as the afterimage was clear, then to close their eyes briefly to end the trial. The large afterimages remained clear for 20–30 sec for most trials. For the two *large afterimage* conditions, subjects dark adapted for a minimum of 15 min before each block began, and rested until the afterimage from the previous trial had faded (typically 2–4 min). In the *small after-image*, and *dark* conditions, subjects light adapted for at least 1 min between trials to ensure that the infrared measurement beam remained below threshold in peripheral vision.

In the *extended afterimage* and *small afterimage* conditions, subjects were instructed to report any perceived movement of the afterimage. In the condition with *extended afterimage with visible reference*, they were asked to report any movement of the afterimage and/or of the visible reference point. In order to correlate perceived position of the LED to measured eye position, the LED was turned off briefly (500 msec) every 8 sec during some of the trials with the extended afterimage and visible reference. The subjects were instructed to remember the apparent position of the LED each time it was turned off momentarily. After the trial, they were asked to mark the remembered positions of the LED on a replica of the bullseye target provided at the end of the trial. Typically, they had to remember three positions during the trial (the number varied based on how long the afterimage lasted).

Control experiment

A control experiment was run after the main experiment to determine the subjects' accuracy in remembering and reporting the relative positions of the LED during the trial. In the control experiment, the bullseye target was displayed on a CRT, along with a red spot that drifted across the screen at mean velocities of 0.2–2.0 deg/sec, mimicking the perceived motion of the LED in the condition with the *extended afterimage and visible reference*. As in the experimental condition, it "blinked off" for 500 msec every 8 sec over each 30 sec trial. After another 5 sec, the subject was asked to report the remembered locations of the red spot on a bullseye replica. (This was the approximate time required in the trials with the *extended afterimage with visible reference* for the subject to get off the bite-bar and pick up a pen.)

Subjects' ability to maintain fixation in complete darkness was also measured. This condition was identical to the *extended afterimage* condition, except that the electronic flash units were not fired when the fixation

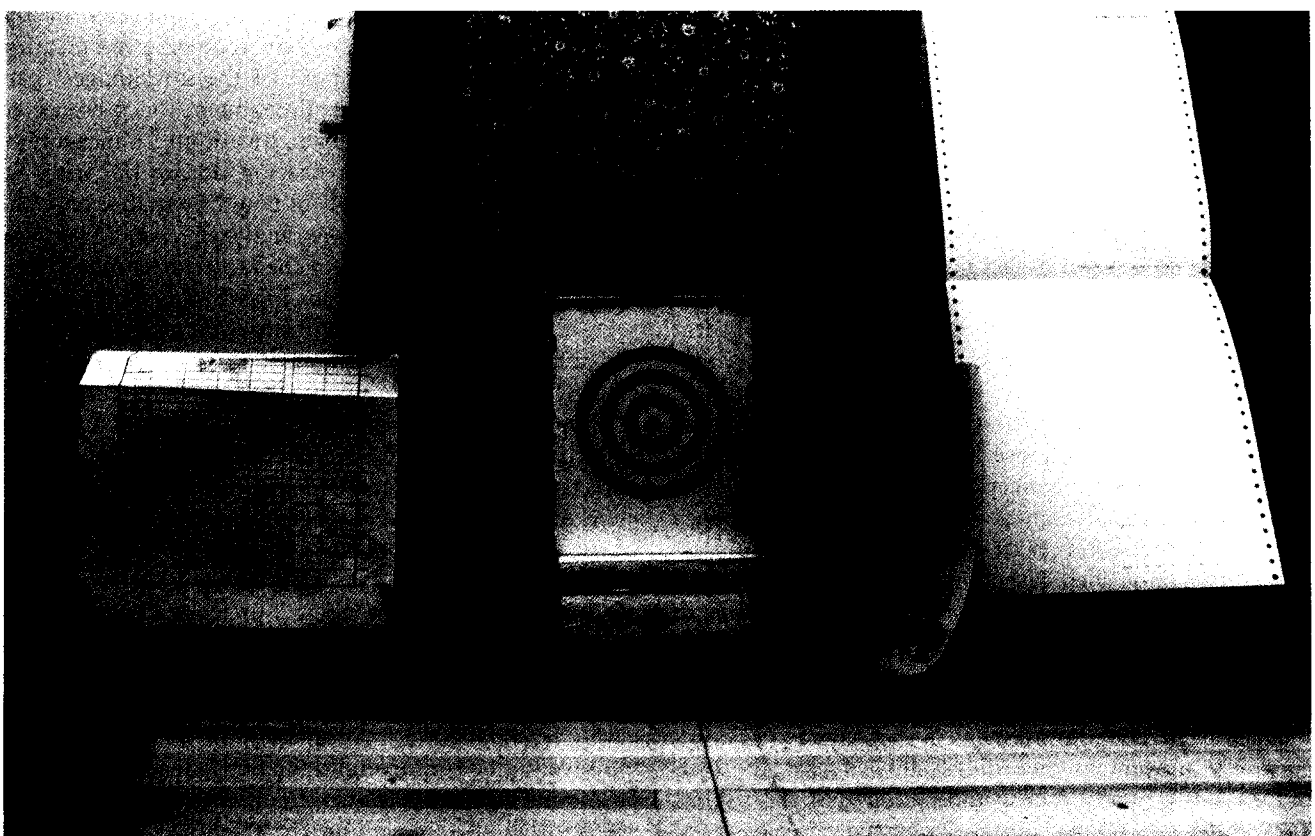

FIGURE 1. Scene illuminated by electronic flash units to produce extended, positive afterimage. The center of the "bullseye" target was illuminated by a small LED (subtending 20 arc sec) to allow steady fixation before the strobes were fired. In the *extended afterimage* condition, the LED was turned off at the instant the strobes were fired.

LED was turned off. Subjects were again instructed to attempt to maintain their direction of gaze throughout the 30 sec trial. Because no visual feedback about the position of the eye is available in the dark, the *dark* condition provides a "base-line" measure of the subjects' ability to maintain their gaze based only on extra-retinal signals, and thus an estimate of the accuracy of the extra-retinal eye position signal.

The final (*visible reference*) condition measured subjects' ability to maintain fixation on the visible reference spot in the absence of an extended afterimage. Subjects were instructed to maintain fixation on the reference spot for 30 sec.

For three subjects, a minimum of 10 trials were run in each condition. For one of the subjects (JP), about 50 trials per condition were run. On another subject (AM) 31 trials were collected only in the *extended afterimage* condition. In addition, informal reports about the afterimage movement were obtained on more than 10 observers whose eye movements were not recorded.

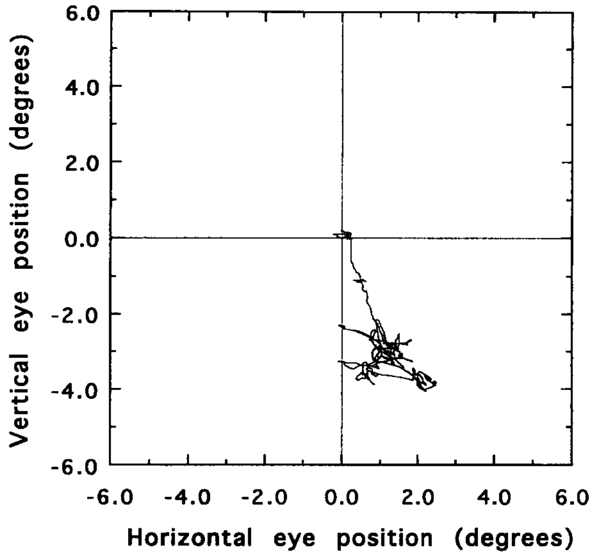

FIGURE 2. Typical *X*, *Y*, eye position trace for the *extended afterimage* condition for observer MH. The subject viewed an extended afterimage for 30 sec. Although the eye was displaced over 4 deg in this trial, the subject reported no perceived motion.

RESULTS

Appearance of the afterimages

Unlike the familiar afterimages caused by momentary glimpses of the sun, or looking directly into a photographic flash, the positive afterimages in the *extended afterimage conditions* yielded vivid, strikingly realistic images. The afterimages took about 1–2 sec to develop after the flash exposure, and lasted about 20–30 sec when the subject was dark adapted. The time–course of the development of the afterimage was very regular, both from one trial to the next and between observers. We have not yet found an observer who does not experience these vivid afterimages. The afterimages of the desktop, the bullseye target, and nearby items were remarkably realistic. Naive subjects found it hard to believe at first that the scene was not in fact illuminated by a dim light, and that one could not reach out and grasp the objects in view. It is doubtless crucial for the appearance of these afterimages that the flash exposure is very brief, so that the image is not smeared on the retina. Large eye movements, i.e. looking from floor to ceiling, will cause the afterimage to "collapse" into a fuzzy, luminescent appearance without perceptual structure. While the robustness of the afterimage to this kind of disturbance varies from one observer to another, as long as subjects did not attempt such large changes in gaze the afterimage appeared very stable, as if it were a real scene, in contrast to the "jiggling" appearance reported with small, localized afterimages.

Despite the percept of constant visual direction, and the lack of perceived movement of the extended afterimages, eye movement recordings showed that the eyes moved substantially during the period that the subject viewed the afterimage. Figure 2 showed a typical two-dimensional eye position trace for a 20 sec period in the *extended afterimage* condition. Figure 3(a) shows the corresponding horizontal and vertical eye position plotted as a function of time. In studies of ability to control fixation of a visible target or to maintain gaze in the dark, it is common to measure the SD of eye position over time (Skavenski & Steinman, 1970). Our focus was different; rather than attempting to describe subjects' ability to maintain gaze, we were interested in the relationship between eye position and perceived location of those afterimages. Because of the afterimages' perceived constancy of visual direction in the presence of relatively large eye movements, we adopted a measure of maximum deviation from fixation during the trial. So that a meaningful comparison could be made, only the first 18 sec of each trial was analyzed. The 18 sec was selected because nearly all of the larger afterimage trials lasted a minimum of 18 sec. Figure 4(a) shows a histogram of the maximum deviation (Δ_{max}) on each trial for subject JP (on whom most data were collected), measured over 29 trials in the *extended afterimage* condition. The mean deviation was 5.3 deg, and even with deviations of more than 10 deg, the afterimage appeared stable. Subjects reported no afterimage movement or change in egocentric direction over a total of 62 trials. The lack of change in afterimage position was also demonstrated informally on more than 10 subjects without eye movement recordings. Subjects often expressed surprise at how far their gaze had drifted when the room was re-illuminated at the end of the trial.

In the condition with the *extended afterimage with visible reference*, the fixation LED in the center of the bullseye target remained illuminated after the electronic flash units were fired. In this condition, subjects saw both the positive afterimage and the reference LED. Figure 3(b) shows a typical eye position trace in this condition, and Fig. 4(b) shows the distribution of maximum deviations across 52 trials for subject JP. The distribution of

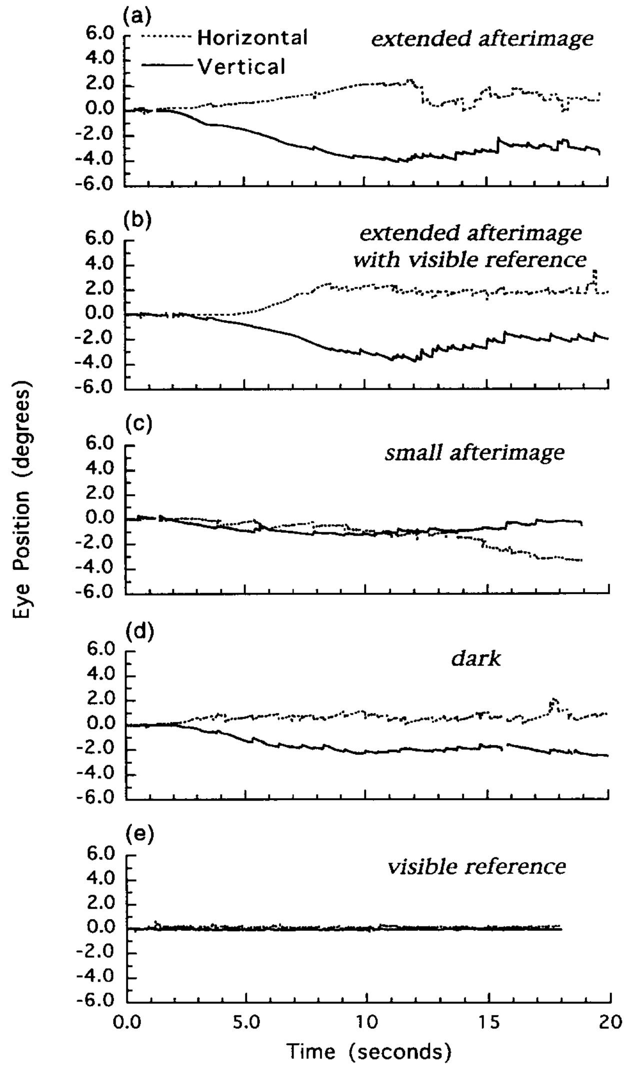

FIGURE 3. Sample horizontal and vertical eye position as a function of time for the five conditions (subject MH). In the *extended afterimage* condition (a), the subject viewed an extended, positive afterimage created by two photographic strobe units. An LED fixation marker in the center of the "bullseye" target was turned off at the instant the strobes fired. In the *extended afterimage with visible reference* condition (b), the LED was visible throughout the trial, along with the extended afterimage. In the *small afterimage* condition (c), a small (20 arc min) afterimage was created by back-illuminating the target center. As in the *extended afterimage* condition, the LED was turned off when the strobe fired. In the *dark* condition (d), no afterimage was present and the subject was in complete darkness after the fixation LED was turned off. In the *visible reference* condition (e), subjects simply fixated the LED without any afterimage. Strong afterimages remained for at least 18 sec in nearly all the afterimage trials, so analysis was restricted to that duration for all conditions.

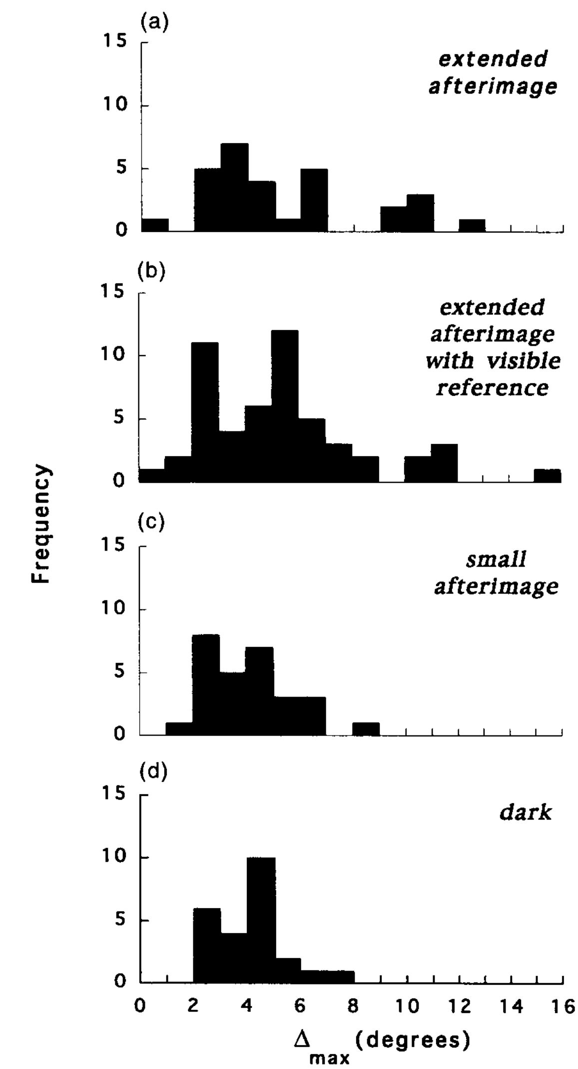

FIGURE 4. Frequency histograms of maximum angular deviation (Δ_{max}) from initial gaze direction for subject JP in all conditions. Subjects reported no apparent movement of the afterimages in the *extended afterimage* (a) or the *extended afterimage with visible reference* conditions (b), although there was a central LED reference visible the second condition; the relative motion caused by the large eye position deviations were assigned to the reference LED. In the *small afterimage* condition (c), a small, central afterimage resulted in smaller maximum deviations, yet subjects reported that the small afterimage was moving, even in the absence of a visible reference. The *dark* condition (d) shows baseline performance for the subject attempting to maintain stable gaze in the dark.

maximum deviation in eye position during the trials is similar to that in the *extended afterimage* condition.

These eye movements resulted in relative motion between the vivid afterimage fixed on the retina, and the LED, whose position on the retina changed due to the eye movements. However, in 146 of 147 trials with six subjects, the perceived motion was attributed to the LED; the larger afterimage was perceived as stationary (in the remaining trial, the subject reported that both the afterimage and the LED appeared in motion). The percept of the stable afterimage dominated, in spite of the fact that subjects were aware that the LED was actually fixed in space. This knowledge did not reduce the illusion of its movement through the apparently stable afterimage. [Note that, unlike the autokinetic effect, the motion of the LED occurs immediately and is closely linked to the eye movements, as described below (and see Levy, 1972; Power, 1983).] As in the *extended afterimage* condition, the apparent motion of the LED was demonstrated informally on over 10 subjects without eye movement recordings.

It was expected that the reported location of the LED would be a 180 deg reflection of the eye position; e.g. when the eye position was above and to the right of the fixation point, the perceived location of the LED would be below and to the left of center. In fact, the positions reported by subjects showed significant variability from that prediction. Figure 5(a) shows the distribution of errors, where error is taken as the difference in distance and angle between measured eye location (reflected 180 deg) and the remembered locations reported after the trials. The errors are plotted with the directed distance between measured and reported radii from the center of the bullseye plotted along the horizontal axis, and the angle between the measured and reported angles along the vertical axis. Positive distance errors occurred when the reported position was farther from the center than was the measured eye position. Positive direction errors occurred when the reported position was rotated counterclockwise from the measured position. Figure 5(b) shows the distribution of errors from the control experiment in which subjects reported the remembered location of a red spot drifting across the bullseye on a CRT display plotted in the same manner. The distributions are similar, indicating that the variability in reported position of the LED in the *extended afterimage with visible reference* condition is probably due to the difficulty of remembering and accurately reporting the positions, rather than a significant difference between eye position and perceived location of the LED.

Mack and Bachant (1969) conducted a careful study of the perceived motion of localized afterimages, and observed that it was well correlated with eye movements. We repeated some of these observations here for comparison with the extended afterimages. A typical record of the eye movements in the *small afterimage* condition is shown in Fig. 3(c), and the distribution of maximum deviations for observer JP is shown in Fig. 4(c). While the distribution of maximum deviations is similar in some respects to that in the two *extended afterimage* conditions, an important difference in subjective reports exists. Unlike the *extended afterimage* conditions, subjects reported that the small afterimage was moving, although there was no visible reference. Subjects reported that they were aware of their eye movements, and the eye movement records showed more centering saccades. Data for control of gaze in the *dark* condition are shown in Figs 3(d) and 4(d). Because only extraretinal eye position information is available in this condition, it provides an estimate of the subject's knowledge of eye position through non-visual signals. Figure 3(e) shows a typical trace from the *visible reference* condition, in which the subject attempted to maintain fixation on the visible LED. In all cases, the maximum deviation was less than the 1 deg histogram bin size, so the mean and SE are represented on the summary plots below.

A summary of the eye movement data for three subjects is shown in Figs 6 and 7. The average maximum deviation in each condition is plotted for each subject in Fig. 6, and the average across subjects is shown in Fig. 7. In addition to the large and small afterimage and *dark* conditions, Figs 6 and 7 include the *visible reference* condition, showing subjects' maximum deviation while fixating a visible reference over the 18 sec duration analyzed. (Note that the *maximum* deviation over this period is plotted, not the more usual measure of SD, so the values might at first sight seem rather large.) Figure 6 reveals that, while there is some variation between observers' performance, the eyes appear to stray more from straight ahead in the *extended afterimage* conditions, and less when simply maintaining gaze in the dark. Ability to maintain gaze in the dark presumably reflects the precision of the eye-position signal, so if gaze deviates more in the *extended afterimage* conditions, it implies that this signal is suppressed in the presence of the extended afterimage, or at least given less weight in the computation of visual direction. More important than the differences in eye movements in the different conditions is the dramatic difference in percept reported between the *large* and *small afterimage* conditions. The lack of any perceived change in position of the extended afterimages, despite the larger eye movements, implies

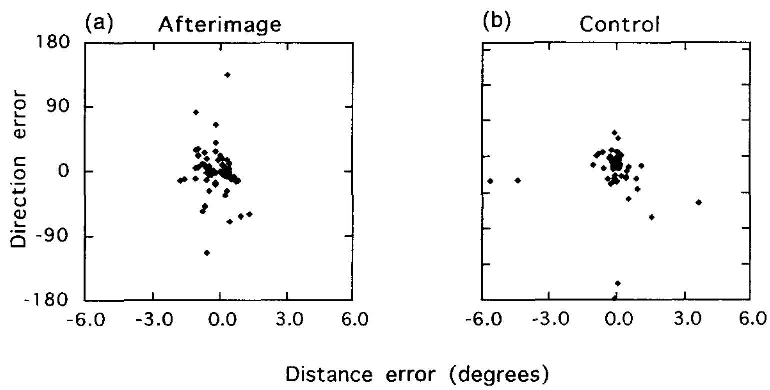

FIGURE 5. Reported position of the visible reference in the *extended afterimage with visible reference* condition were not exact 180 deg reflections of measured eye position. (a) The distribution of distance and direction errors for subjects JP and MH, where error is the difference between reported position and measured (and reflected) eye position. Positive distance errors occurred when the reported position was farther from the target center than was the measured eye position. Positive direction errors occurred when the reported position was rotated counterclockwise from the measured position. (b) Similar measurements for a control experiment in which subjects reported the remembered positions of a red dot viewed in motion across a bullseye target on a CRT.

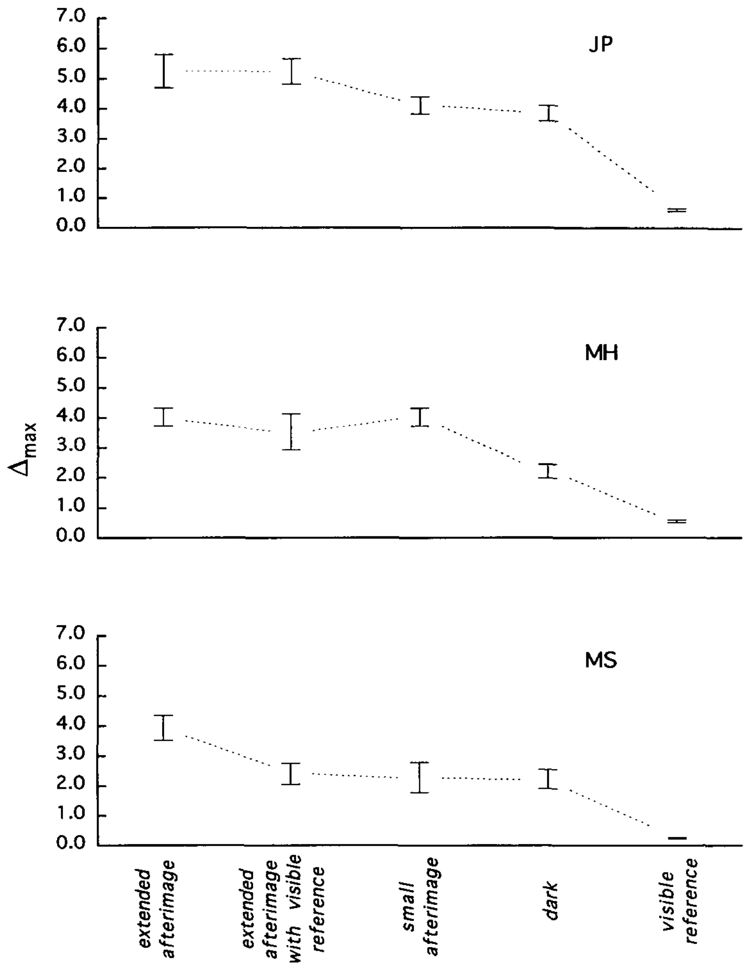

FIGURE 6. Summary of eye movement data for three subjects in all five conditions (see Fig. 3 caption for a description of the conditions). Plots represent the mean value across trials of the maximum deviation from starting position (Δ_{max}). Error bars are 1 SEM.

that there is a "rule change" in the presence of the extended afterimages, favoring the visual information in the determination of visual direction.

Nature of the eye movements

The issues of visual direction constancy and visual stability are to some extent separate. Visual direction constancy is the more general problem, and refers to our ability to maintain localization of objects with respect to the body in the presence of a range of eye and head movements. The issue of visual stability, on the other hand, is usually framed in terms of saccadic eye movements, and concerns the lack of a percept of change in position of objects following a saccade. To some extent these percepts appear to be separable (see e.g. Stevens, Emerson, Gerstein, Kallos, Neufield, Nichols & Rosenquist, 1976), so it is of interest to examine the nature of the eye movements involved here. It was usually the case

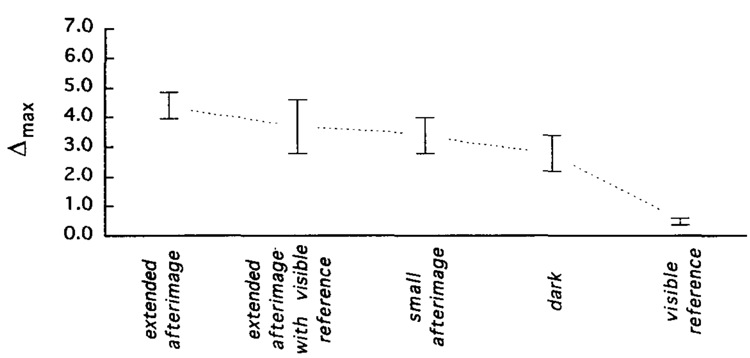

FIGURE 7. Average across subjects of eye movement data in all conditions (see Fig. 3 caption for a description of the conditions). Error bars are 1 SEM between subjects.

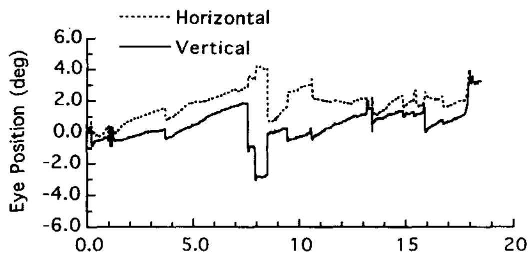

FIGURE 8. Sample horizontal and vertical eye position as a function of time for the *extended afterimage* condition, when instructions to hold gaze were relaxed. Subjects were instructed simply to "watch the afterimage", rather than to maintain their gaze. Subject MH.

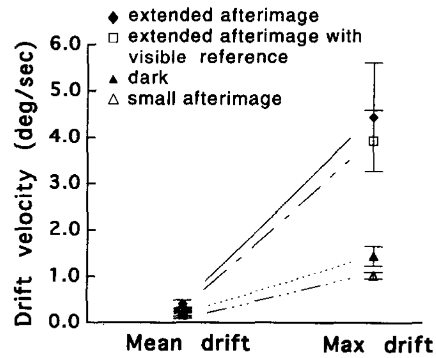

FIGURE 9. Mean and maximum drift velocities for afterimage and dark conditions, averaged across subjects.

that large gaze changes disrupted the structured appearance of the extended afterimages. The eye movement records revealed fairly frequent small saccades up to about 1 deg, which went unnoticed by the observers and were not accompanied by any apparent change in afterimage direction. In order to explore the limits of this constancy of direction and perceived stability in the presence of saccades, we relaxed the instructions to the subjects to attempt to maintain gaze, and simply asked them to inspect the afterimage. This led to the kinds of small saccades typical of exploratory eye movements. Large saccades (e.g. 10 deg) still destroyed the clear afterimage, but some subjects could make moderate saccades (up to about 5 deg) without perceived movement of the afterimage. A sample trace from such a trial is shown in Fig. 8. This trace shows a number of small to mid-sized saccades in an 18 sec period, including a diagonal saccade of over 4 deg. Data were collected for three subjects in the *extended afterimage* condition for 10 trials each under these instructions. As before, the subjects reported no changes in the position of the afterimage despite the frequent occurrence of these larger saccades. Consequently, both visual stability and constancy of visual direction can be maintained by an external reference frame, even in the presence of moderate sized saccades.

Most of the changes in eye position seen when subjects were asked to maintain their gaze direction were accomplished by smooth eye movements. Mostly these were the drift movements ordinarily observed in darkness. However, an examination of the velocities reveals that higher velocity movements frequently occurred. This is shown in Fig. 9, where the mean and maximum eye velocities are shown for the *afterimage* and *dark* conditions. The mean velocities are consistent with previous observations (Skavenski & Steinman, 1970), but the maximum velocities are much higher. In the presence of the extended afterimage the eyes reached velocities of 4–5 deg/sec. It seems likely that in this case the afterimages are generating open loop pursuit which goes uncorrected by the subject despite the instructions to maintain gaze. Open loop pursuit has been observed with small afterimages when they are positioned eccentrically (Carpenter, 1988). This does not appear to have occurred in this experiment, since the maximum drift observed for the *small afterimage* condition is no larger than when no afterimage is present.

DISCUSSION

These experiments demonstrate the importance of the visual context in visual direction constancy. When the image of a complex visual scene is stabilized on the retina the size and velocity of eye movements increase, yet the afterimage does not appear to move with the eye, and erroneous judgments of visual direction are made. When a visual reference is available, relative motion between the afterimage and the reference is attributed to the reference. Since small afterimages do appear to move even with smaller, slower eye movements, it appears that the computation of visual direction depends heavily on the visual context, and that the extra-retinal eye position information is given much less weight in a normal context than in the dark. In the dark, judgments are made with respect to a head- or body-centered frame of reference, and position with respect to an egocentric frame is obtained from a combination of retinal location and information about the position of the eye in the head. In such impoverished environments there is insufficient information to allow use of an external frame. In the absence of that information, the internal frame is used by default.

When experiments are performed in richer environments, the perceptual system need not rely on the extraretinal signals alone; there is a great deal of information available from the image stream itself, which contains regularities at every time scale, in this case rigid translations of the retinal image (Newell *et al.*, 1989). The "regularities" within each view in this disjoint image stream may serve as an "anchor" to fix the environment. Conflicts between this anchor and signals from the vestibular system can cause sea- and airsickness (Rolnick & Bles, 1989). Another indication that knowledge of eye position is not necessary to maintain stability if enough information is present in the retinal image is demonstrated by our ability to interpret successive views in motion picture and television displays, even though explicit descriptions of camera movements are not available (Hochberg, 1978). It is interesting to note that "camera cuts", in which the same object is suddenly seen from a different viewpoint, are not disorienting even though there is no analogous natural movement.

These results complement those of Matin *et al.* (1982), and Stark & Bridgeman (1983), discussed above. In the present experiment, however, it is the visual information which is erroneous, rather than the eye position signal. How is the visual context taken into account? Previous studies (e.g. Skavenski & Steinman, 1970; Karn, Møller & Hayhoe, 1993) in which subjects maintained their gaze in the dark and made eye movements to remembered targets after intervening saccades indicated that the oculomotor system has access to an extraretinal eye position signal. The perceived motion in the *small afterimage* condition (and see Mack & Bachant, 1969) is presumably due to that signal, and shows that perceptual judgments make use of the signal. The extended afterimage conditions led to larger and faster eye movements, yet did not result in perceived motion of the afterimages, so the extraretinal eye position signals must have been suppressed in some way. One possibility is that the absence of retinal slip vetoes the eye position information, since the two sources are in conflict. However, there are indications that instead of a simple veto, there is some linear combination of location specified by egocentric and exocentric reference frames. When asked to direct gaze at a remembered location in the dark, observers appear to average position with respect to the head and position with respect to a visual reference, when these are arranged to be in conflict (Hayhoe, Lachter & Møller, 1992). Matin and Fox (1989) also observed averaging of the effects of visual context and eye and head position signals in judgments of eye level horizontal. It seems likely that the relative weights of the two sorts of information may depend on the complexity of the visual context. In judgments of visual direction, Bridgeman and Graziano (1989) found the greatest influence or "capture", by the visual context with a complex scene.

The fidelity of the eye position signal varies with the type of eye movement, and this may influence the extent of visual capture. Most of the change in eye position we observed was slow drift in the range of 0.1–0.5 deg/sec. Although it is likely that the drift movements associated with maintaining gaze in the dark are not available to the subject, the eye clearly strays much further when the large afterimage is present. It is possible that these movements result from pursuit of some part of the afterimage. This may explain why the deviations were also slightly greater with the small afterimage. Alternatively, it may be the consequence of the failure of an optokinetic system to maintain stable gaze, since retinal slip signals are entirely absent (e.g. Bridgeman & Graziano, 1989). In addition to the slow eye movements, subjects' records also contained frequent saccades. Usually the saccades were small (in the range 0.5–2 deg) and went unnoticed by the subject. This shows that visual capture is also effective in maintaining visual stability across small to moderate saccadic movements. Very large saccades (e.g. 10 deg), including those accompanied by a head movement, usually destroyed the impression of a three-dimensional scene, although a blotchy, formless afterimage still remained. This may indicate the limits of the strength of visual capture in the presence of saccadic eye movements, or might also reflect some saccadic suppression mechanism.

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