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DIRECTION-SPECIFIC AND POSITION-SPECIFIC EFFECTS UPON DETECTION OF DISPLACEMENTS DURING SACCADIC EYE MOVEMENTS*

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Abstract—We examined the probability that a displacement during a horizontal saccade of either of 2 points of light would be detected, as a function of direction (up, down, or in the same or opposite direction as the saccade) and as a function of whether the point was the start or the target for the saccade. Vertical displacements are all easier to detect than horizontal; for horizontal movements detection is determined by an interaction between direction and position; finally, when the *target* objectively moves, subjects very often incorrectly assign the movement to the *start* (but *not* vice versa); this suggests that the *target* for a saccade in these conditions may be assigned as a frame of reference for other perceptual events.

INTRODUCTION

Everybody "knows" that when we make saccades to examine the visible world it seems to remain in the same place despite the substantial shift of its retinal image caused by the saccade. This phenomenal stability has called for explanation, since under other circumstances we clearly do perceive shifting retinal images as objects that are really moving. The explanations proferred tend to fall into two classes, those that emphasize the nature of a "comparator" mechanism that "takes into account" eye movements in perceptually assessing the movements of the retinal image (a tradition stemming from Helmholtz), and those that emphasize the object-relative frame-of-reference provided by the actually stable textured visual environment (Gibson, 1966) with its invariant ordinal spatial relations; perhaps to the latter class can be assigned those theories that posit perceptual assumptions of stability, and the determining importance of prediction in evaluating retinal image change (Mackay, 1972, e.g.). In order to evaluate the correctness, or better the completeness, of these two classes of explanation, it is necessary to use artificially restricted conditions in which only one (the comparator mechanism) can operate, and two kinds of hypothesis can be proposed, premised upon its successful operation under such conditions: firstly, that spatial localization of visual events in the context of eye movements should be accurate, and secondly that, therefore, the perceptual system should be able reliably to distinguish veridical movements of visual targets in space from movements of their images consequent upon eye movement.

Experiments to investigate the first of these hypotheses have been extensively carried out (cf. Matin, 1972; Mackay, 1973; Mateef, 1978; Mitrani *et al.*, 1979, for discussion and data) and they show that spatial localization is substantially disturbed in the context of eye movements in reduced cue conditions, or in the dark. The conclusion drawn has been that perception has access only to a weak and delayed extra-retinal signal about eye movement. However Bischof and Kramer (1968) have gone further in showing that the extent of mislocalization during saccadic eye movements is related to the retinal location of a test flash, thus suggesting that the recomputation of a frame of reference associated with saccades may not be uniform, but related to the *functional importance* of different retinal zones.

Experimental tests of the second hypothesis have shown that the perceptual system is rather bad at correctly identifying a veridical target movement when it occurs simultaneously with a saccade-induced shift of the retinal image (Beeler, 1967; Mach, 1970; Bridgeman *et al.*, 1975; Stark *et al.*, 1976; Whipple and Wallach, 1978; Festinger and Holtzman, 1978). This failure may not be construed as a failure of discrimination but as a failure of detection, since the converse finding, that a displacement of the target in the absence of an eye movement may be registered as an eye movement, has not apparently been established. The reports referred to above all concur that when a target moves during a saccade it is less likely to be detected than when it moves during fixation, thus indirectly supporting the idea of "assumed stability". Only when the target moves a substantial fraction of the distance the eye travels is it reliably detected.

The relations between the results of these experiments and the ideas expressed by Bischof and Kramer are not clear. None of the experiments have

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attempted to investigate whether differences in detectability of displacement exist at different spatial or retinal locations (though Mitrani *et al.*, 1970, do support the idea that saccadic suppression of a light flash differs at different retinal locations at a given time relative to the saccade). Bischof and Kramer's results show that when an eye movement imposes a reassignment of spatial values to retinal locations, locations differing in functional significance are assigned new values at different rates, suggesting that whatever computations are being made on the basis of an extra-retinal signal are not made uniformly for all locations at the same time. Even without these results, it seems *a priori* possible that sensitivity to displacement might be different at a zone that is functionally significant both for the oculomotor system and for vision, such as the saccade's target, than at some functionally irrelevant zone of an equivalent retinal eccentricity.

A second surprising aspect of the data on detectability of displacements concerns the finding (Mack, 1970; Bridgeman *et al.*, 1975; Stark *et al.*, 1976) that displacement vector is unimportant: thresholds generally are raised, and direction and indeed congruence of the displacement with respect to the saccade during which it occurs matters little. True Whipple and Wallach (1978) reported that thresholds for detecting orthogonal movements were higher than those for congruent displacements, but, as Bridgeman and Stark (1979) point out, this may be artefactual. Only Festinger and Holtzman (1978) in a rather different experimental paradigm suggest that orthogonal movements of a target during eye movement yields different percepts from congruent movements, and their data suggest that orthogonal movements are *better* perceived. Since it would appear *a priori* that detectability of displacement of a visible object during a saccade should be related to the degree to which it is easily confused with the image shift caused by the saccade, we might expect that displacements that are vectorially very different from the saccade vector should be more easily detected than those that are the same or very similar. The failure of previous workers to confirm this seemingly obvious intuition is, to us, surprising; even if Whipple and Wallach's results are not attributable to artefact, they are in the wrong direction. Festinger and Holtzman alone seem to confirm our intuitions.

We have carried out a number of experiments, of which one will be reported here, specifically to examine whether displacements at different spatial locations are equally difficult to detect during saccades, and whether displacements in different directions at these locations are equally easy to detect. Our premisses were that any functional extra-retinal signal assigning spatial values to retinal locations would show non-uniform effects throughout retinal space and that because the computations associated with this extra-retinal signal would be vectorially bound to the eye movement that generated it, displacements in other vectors than the saccade's would be easier to detect independent of any retinal effect.

EXPERIMENTAL METHODS

Subjects were tested in a dark room, their heads restrained by a conventional dental bite-bar and forehead rest. In front of them, at eye level, was a Tektronix 604 display CRT (P31 phosphor) mounted in a mask that left visible only the screen. Horizontal movements of the right eye were recorded using an infra-red photo-electric method controlled by computer (C.A.I. Alpha LSI 2) which sampled eye position at 500 Hz. The recording system bandwidth was 330 Hz, and resolution was about 6 min arc. Saccades were detected in real time by the computer when eye velocity rose above a criterion that was adjusted individually for each subject (the mean value was about 70°/sec); saccades were used to trigger changes in the display where necessary. Horizontal eye movements were recorded and stored for subsequent analysis Latencies of initial and correction saccades, together with direction and amplitude of correction saccades were examined for relations to detection of displacements.

Each trial started with the appearance of a spot on the screen, randomly positioned within a 3.2° range on the left or right. After a randomly varying interval, a second spot appeared on the other side of the screen at a distance randomly varying between 4.37° and 5.24°, and at a predetermined moment one of the spots displaced instantaneously in 1 of 4 directions (up, down, left or right) by 1 of 4 distances (8.3, 12.5, 16.5 and 25% of the interspot distance). After a further 1 sec both spots were extinguished. Spot brightness was about $\overline{0.35}$ log ft-L. The subjects had three response buttons and on every trial had to indicate by pressing appropriately whether they had seen the left spot, or the right spot or neither of the spots move.

The percentages of displacements that were not detected, that were correctly detected or of detections that were in error were calculated and were related to the experimental conditions. The experiment permitted subjects to set a high criterion for detection: in a subsequent control experiment (see below) the false positive rate was correspondingly very low (as indeed it was in pilot experiments).

Four subjects (all psychology undergraduates, 3 females and a male, naive with respect to the experiment and about eye movements) were each tested for 3 sessions. Each session was of 256 trials (16 blocks of 16 trials), with equal numbers of each experimental combination within and across sessions.

RESULTS

Although differing in their absolute levels of performance, subjects showed broadly similar patterns of responses, and their data are therefore presented both

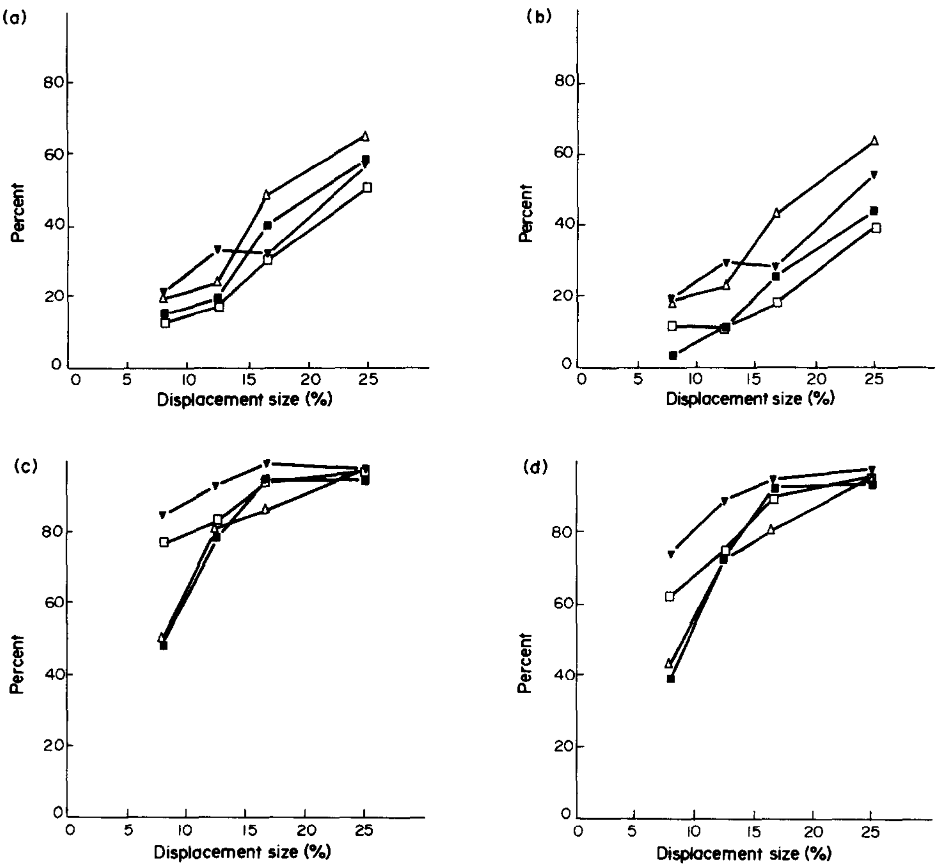

Fig. 1. A. Percentage of horizontal displacements detected (pooled data) during saccadic eye movements. Symbols: △—start moves in same direction as saccade; ▼—start moves opposite to saccade; □—target moves in same direction; ■—target moves opposite. B. Percentage *correct* detection of horizontal displacements (pooled data) during saccadic eye movements. Abscissa: displacement magnitude as % of interspot separation. Symbols as in Fig. 1A. C. Percentage of vertical displacements detected during saccades (pooled data). Symbols: △—start moves up; ▼—start moves down; □—target moves up; ■—target moves down. D. Percentage of vertical displacements correctly detected during saccades (pooled data). Symbols as for Fig. 1C.

pooled and separately. Figure 1 shows for the pooled data the percentage detected and the percentage correct for horizontal and vertical displacements. The most obvious point is that there is no overlap between the curves for horizontal and vertical displacements, vertical displacements being easier to detect at all displacement magnitudes. Secondly, there is little difference between percent of vertical displacements detected and percentage correct, whereas there is a rather large difference between percentage detected and percentage correct in the case of horizontal displacements.

We wished to know if the different position-by-direction combinations yielded reliably different detection patterns and so we simply counted the total absolute numbers that were *not* detected and that were *correctly* detected for the different combinations collapsed across displacement magnitude and carried out a χ^2 test for equality of frequency, using the null hypothesis that the frequencies for different conditions would be equal. There is no likelihood that any one horizontal combination will be more easily detected than any other ($\chi^2 = 3.84$, NS), whereas there is a significant probability that movements of the *start* will be more often *correctly* detected than movements of the target, regardless of direction ($\chi^2 = 33.95$, $P < 0.01$). For vertical displacements, however, movements of the virtual line between the two points when the start moves up, or target moves down are *less* easily detected than movements in the opposite sense. ($\chi^2 = 40.82$, $P < 0.01$), and the same is true for correct detections ($\chi^2 = 10.31$, $P < 0.01$).

These differences between detections and correct detections are made more explicit by Fig. 2 which shows the percentage of detections which are *misattributed* (i.e. where a subject correctly detects a displacement but ascribes it to the wrong spot). It is clear that there are no significant differences in misattributions for different conditions of vertical displacements ($\chi^2 = 2.06$, NS); for horizontal displacements, on the other hand, target movements are significantly more likely to be misattributed to the start than vice versa

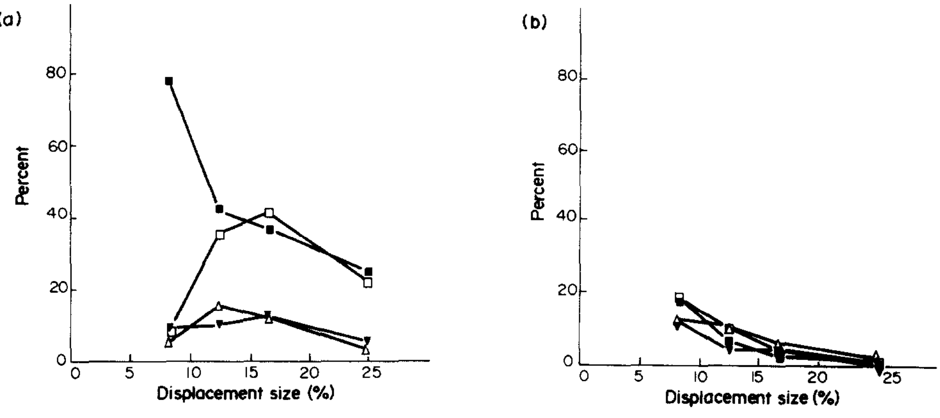

Fig. 2. A. Percentage of detections of horizontal displacements that are *misattributed* (pooled data). Symbols as for Fig. 1A. Abscissa: displacement magnitude as percentage of interspot separation. B. Percentage of detections of vertical displacements that are *misattributed* (pooled data). Symbols as for Fig. 1B.

($\chi^2 = 30.83$, $P < 0.01$), an effect that is particularly pronounced if the target movement is in a direction opposite to the eye movement.

Some idea of individual variability and similarity can be gained from Fig. 3 in which the percentage correct for horizontal displacements is given for the four subjects separately. One subject, S.J., shows a pattern which is quite idiosyncratic, but the remaining 3 subjects show substantially the same ordinal relations between different conditions, though at different levels of performance. (Given the effective absence of false positives, the notion of chance levels of responding in these curves can be ruled out).

Eye movement data from the last 2 sessions of this experiment were analysed to examine relations between subjects' responses and the occurrence of correction saccades, their latency, amplitude and direction. The data are presented in Table 1 which shows the overall incidence of correction saccades classified by subjects' responses when displacements were horizontal. There does not seem to be any clear-cut relationship between parameters of eye movements and detectability of displacements. Certainly there is no effect of the latency of either the initial or the correction saccade upon the likelihood of detection and for the two subjects who performed best in the detection task there is no effect either of incidence, or direction or amplitude of correction saccades. For the 2 subjects with lower rates of detection, there are suggestions that the pattern of correction saccades is different upon trials when detection occurs; that detection is related to the absence of correction saccades, or to large deviations of correction saccade amplitudes from those found on trials with no detection. It appears that for the two subjects who are performing less well, the occurrence of correction saccades (unless they are distinguished by marked deviations in amplitude) tends to introduce uncertainty and hence a higher likelihood of failure to detect: the absence of this effect in the other 2 subjects may reflect an ability to focus attention on other cues in the solution of the task (particularly perhaps visual ones: it is notable that overall these two subjects produce higher levels of misattributions, suggesting a greater dependence on object-relative information). In any case, correction saccades do not seem to produce a useful cue to the occurrence of a displacement, and may be a source of confusion.

Control experiment

In order to establish more precisely the role of eye movements themselves in the results we have just described, we subsequently carried out a control experiment, under the same conditions except that subjects

Table 1. Percentage of trials (sessions 2 and 3) with horizontal displacements on which correction saccades occur, classified by S's response

	Subject's Response		
Subject	Correct detection (%)	All detection (inc. misattributions) (%)	No detection (%)
S.J.	27	26	31
S.R.	34	34	31
A.C.	51	58	80
R.J.	9	12	34

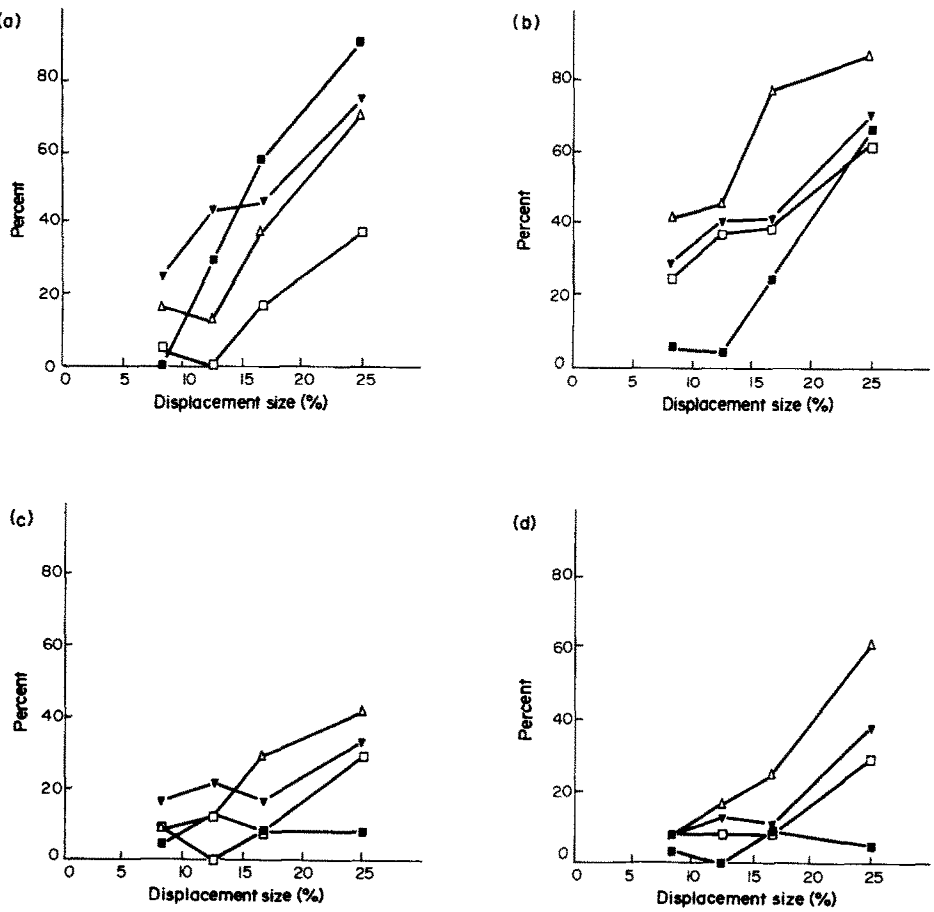

Fig. 3. Percentage correct detection by individual subjects for horizontal displacements during saccades. Conventions as for previous figures. A. subject S.J. B. subject S.R. C. subject A.C. D. subject R.J.

were instructed *not* to move their eyes, but to maintain fixation on the first spot to appear. We also included a no movement condition in order to monitor the false positive rate.

On each trial, therefore, a spot appeared, as before, to the left or the right of the screen. After an interval randomly varying between 1 and 2 sec, a second spot appeared, and on 75% of the trials, after a second interval randomly varying between 400 and 600 msec one or other spot displaced. Displacements were set to be either 5, 10 or 15% of the separation between the spots, and could be in any of the same four directions as in the previous experiment. On the remaining 25% of trials no displacement occurred. Subjects were required to indicate, as before, whether the left or the right or neither spot displaced. Subjects were not informed of the no movement condition.

Four subjects were run, 2 of whom had participated in the original experiment (subjects S.R. and A.C.) and 2 of whom were naive. All subjects were tested for 2 sessions of 320 trials each. The data were analysed as before. Eye movements were not recorded but were monitored to ensure correct fixation.

RESULTS

The results for the four subjects are presented in Fig. 4. It is clear that when no saccades are made, there are no significant failures to detect either horizontal or vertical movements as large as 10% of the spot separation, nor indeed is there any difference between foveal and peripheral detection of these magnitudes. As we should expect, at the smallest magnitude of displacement, peripheral detection tends to be worse than foveal, though this is not uniformly the case.

The rate of false positives in the set of data pooled across all subjects is 1.6%, sufficiently low to give us confidence that in the present experimental conditions, subjects set a high criterion for detecting displacements. The misattribution rate (detections incorrectly ascribed to the wrong point) was less than 0.5% of all detections, and these few were distributed throughout different conditions of displacement.

In conclusion, when the eyes do not move, much smaller displacements can reliably be detected, and there are no indications of directional or positional effects in the data.

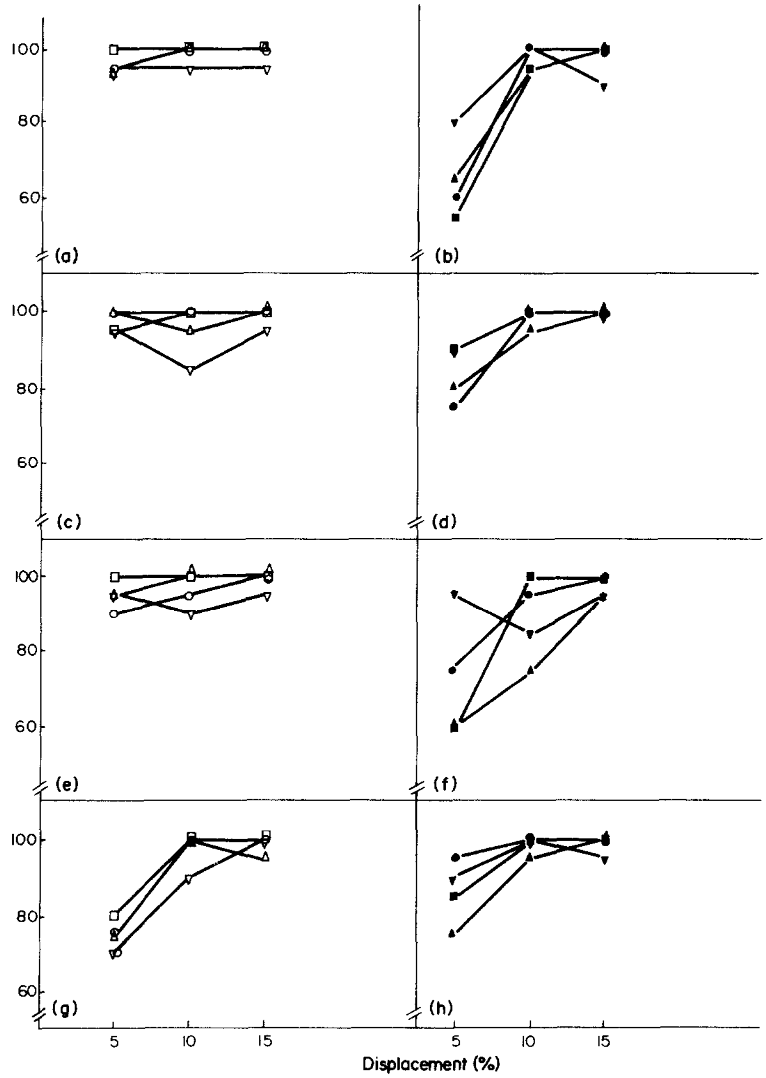

Fig. 4. Percentage of detections by four subjects in the control experiment (i.e. with *no* saccades). Open symbols: foveal spot moves. Filled symbols: peripheral spot moves. Symbols: ○—upwards; □—downwards; △—towards other spot; ▽—away from other spot. A & B. Subject A.F. C. & D. Subject S.R. E. & F. Subject A.C. G. & H. Subject P.C. (Subjects S.R. and A.C. participated in the main experiment).

DISCUSSION

Our experiments confirm that saccadic eye movements lead to difficulties in detecting displacements of small spots that occur while the eyes are in movement. More interestingly, they suggest that these difficulties are related both to the direction of the displacement and to the position of the displaced spot. We shall first discuss one alternative interpretation of these directional effects and then consider our results in relation to those of other workers.

The differences we have found between detectability of horizontal (congruent) and vertical (orthogonal) displacements could be interpreted as a difference in discriminability of orientation change as opposed to length change in the virtual line connecting the two spots. It is, therefore, *prima facie* not certain that this particular aspect of the results does need to be referred to the vector of the eye movement except insofar as differences exist, for both horizontal and vertical displacements, between functionally differentiated points. It must, however, be pointed out that the results of the control condition do not suggest that vertical displacements in the absence of eye movements are more easily detected than horizontal; the results are, therefore, at least compatible with the hypothesis advanced in the introduction that displacement orthogonal to the eye movement is more easily and more correctly perceived than that which is congruent with it. In this we are in agreement with Festinger and Holtzman (1978).

Further, reflection suggests that the discrimination of the orientation of a line in space under reduced cue conditions cannot be carried out independently of some knowledge of torsional eye position. The marked superiority in detectability for vertical displacements when the start moves up or the target down (a movement that in physical space is clockwise when the eyes move right, and counterclockwise when the eyes move left) can possibly be related to Donder's Law, given that *the display in these experiments is located above the projection of the retinal horizontal meridian when the eye is in the primary position.* Thus when the eye fixates on the left, for example, it will show a degree of upward and outward rolling that will shift the retinal image downwards and inwards, in the direction of worse detection.

It remains to discuss the discrepancies between our results and those of other workers. Unlike them, we report both directional and position-specific effects on detection rates for displacements during saccades. We think these differences can be attributed mainly to methodological variables. In the first place, we have not been trying directly to measure absolute thresholds for detection. We did not use forced choice procedures, nor did we systematically attempt to find a critical threshold value of displacement magnitude. Rather we asked: "Is there a difference in detectability of displacement under different conditions, *given that a subject is satisfied she has detected a displacement*?" It is quite possible that more rigorous application of forced choice procedures would reveal a "threshold" at which these phenomenal differences vanish. (Our subsequent experiments, in which we have used forced choice techniques do not, however, appear to support this view).

Secondly, unlike Mack (1970), Whipple and Wallach (1978), or Festinger & Holtzman (1978), we did not yoke the movement of our display to the movements of the eye. In our experiment, the displacements were effectively instantaneous. This of course provides quite different offset and onset information to the visual system from that produced by movements whose dynamics are those of the eyes themselves. Bridgeman *et al.* (1975) and Stark *et al.* (1976) also used very fast displacements, but their subjects were constrained to detection only (i.e. did it move or not?) and were given a forced choice procedure.

However, the most important difference in our view is that in our experiments the visual array (such as it was) was discrete and separately articulated. There were *two* separate and separable points in view, whereas in *all* the preceding experiments only one visual stimulus has been presented and it has moved *uniformly* during the eye movement. This has been true both for a spot (as in Mack's experiment, in which it was always the start for the eye movement), and for a large structured array in the case of Bridgeman *et al.* The use of such indivisible arrays clearly eliminates the possibility of object-relative phenomena, and is unable in principle to answer questions about a functionally differentiated field.

And what of the stability of the real world during saccades? We agree with almost everybody that only if a rather large displacement occurs during an eye movement can a subject reliably detect it: the clearly high frequency with which subjects fail to report displacements does not argue for an efficient extra-retinal signal that can establish the veridical position of objects in space except at a crude level. The object-relative effects we have found are compatible with the idea that localization proceeds in terms of spatial relations within the visual array and its elements. Nevertheless, we believe our results do establish one retinal effect which may depend upon an extra-retinal signal: a specific shift in the organization of the frame of reference for stability to the target of the eye movement, an effect that precedes the redeployment of the fovea to that location.

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