SMALL STEP TRACKING: IMPLICATIONS FOR THE OCULOMOTOR "DEAD ZONE"

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RASHBASS (1961) reported in an influential study of eye tracking that "there is a threshold target displacement. Target displacements smaller than this produce no responding saccadic movement. This threshold is about 0·25–0·5° in size."[1] Rashbass' finding has been widely cited but seldom questioned despite the problems it raises for understanding oculomotor control during maintained fixation of a stationary target.

One exception is ALPERN (1969) who points out that CORNSWEET's (1956) finding that saccades reduce extremely small position errors argues against the broad "dead zone" described by Rashbass. The oculomotor system keeps a stationary fixation target within the foveal bouquet during maintained fixation, never allowing more than a very few minutes of arc of fixation error to build up before initiating a saccade that returns the line of regard to the center of the target image. Therefore, when the fixation target is displaced by a very small amount (introducing a small fixation error), the oculomotor system would be expected to respond by moving the eye in the direction of the displaced fixation target until the target again falls at the center of the foveal bouquet. However, the Rashbass finding that target displacements smaller than 15–30′ produced "no responding saccadic movement" indicates that fixation errors introduced by a sudden movement of the target are somehow different from fixation errors produced by the oculomotor system itself. How the oculomotor system would make such a distinction is not obvious.

Recently, TIMBERLAKE, WYMAN, SKAVENSKI and STEINMAN (1972) concluded in a study of the oculomotor error signal in the fovea that "The oculomotor 'dead zone' is surely smaller than 10′ and may even be less than 5′—smaller than the 0·25–0·5° 'dead zone' reported by RASHBASS (1961) with similar stimulus conditions". This paper confirms the Timberlake *et al.* speculation by demonstrating that the fixating eye consistently and accurately corrects target displacements as small as 3·4′.[2]

METHOD

Recording

Horizontal and vertical eye movements were recorded with the two-dimensional contact lens optical lever pictured in Fig. 1. This eye movement recording system, described elsewhere (HADDAD and STEINMAN, 1973),

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[1] BENNET-CLARK (1964) also reported a saccadic "dead zone" of the type described by Rashbass in a subsequent tracking experiment. It is interesting to note, however, that Bennet-Clark's results showed that some of his subjects were able to compensate for target displacements of less than 10′ within 1″ of the displacement. Nonetheless, Bennet-Clark states that "allowing for experimental differences in conditions" his data are in agreement with the data which Rashbass uses as evidence for a "dead zone" of 15–30′. Bennet-Clark himself concludes from his data that "The hypothesis of an oculomotor 'dead space" proposed by FENDER and NYE (1961) receives some support but the size of the 'dead space" varies from subject to subject."

[2] The results of this experiment were first reported by WYMAN and STEINMAN (1971).

records small rotations of the eye free from contamination by torsions of the eye or translations of the head. The recording limits were 1° on each meridian with the optical lever length used, permitting resolution of eye position to about 3″.

Stimulus

The fixation target was a sharply focused green point on the face of an oscilloscope, seen in darkness. The point was produced by a short persistence phosphor (P-20) whose intensity was set to be about 1·6 log units above absolute foveal threshold. Care was taken to eliminate any distinguishable features from the oscilloscope face which subjects could have used as reference marks to aid in identifying displacements of the target. The target was located 2·04 m directly in front of the subject's right eye and was less than 2′ in extent at this distance. The left eye was covered and closed and the head was held rigidly in place by means of a dental acrylic bite board.

Subjects

Two subjects participated in the experiment. One, RS, was very experienced in wearing the contact lenses used in this method of eye movement recording and had previously served as a subject in many psychophysical and eye movement experiments. The second subject, GH, had never served in a visual psychophysical or eye movement experiment. She reported that she had never previously practiced keeping her line of regard on a very small target. The subject's contact lenses were corrected for distance vision.

Procedure

Subjects were instructed to stay on-target throughout each 11·5 sec trial and to correct for any change in target position. The subject started each trial when he felt that he was ready and on-target. Trials began with 5 sec of fixation of a centered target. After 5 sec, the target stepped, unpredictably, either 1·7, 3·4, 6·9, or 13·8′; up, down, right or left (size and direction were randomly determined). Steps always occurred 5 sec after the trial began and their onset was accompanied by an auditory signal—a clearly audible relay click. Each trial ended after 6·5 sec of fixation of the displaced target.

We designed our circuitry so that the digital output of our recording system showed fixation eye position averaged over a 5-sec period. We measured average eye position for the 5 sec before the target step (pre-step average) and for the 5 sec period beginning 1·5 sec after the target step (post-step average). The 1·5 sec period immediately after the target step was excluded so that the transient state, during which the eye changed its position, would not be included in the post-step average. The difference between the pre- and post-step averages describes the shift in steady-state fixation eye position caused by the target step.

RESULTS

The eye almost always moved in the same direction as the target

For the experienced subject, RS, 119 of the 120 trials, (99 per cent) recorded with 3·4′ or larger target steps were corrective in the sense that his average eye position during the last 5 sec of the trials was displaced in the direction of the target step. The smallest step (1·7′) was corrected 65 per cent of the time (27 of 40 trials). Even this result is statistically significant (only 25 per cent would be expected by chance, because the target moved in 4 directions and $\chi^2 = 29{\cdot}3$, $df = 1$, $p < 0{\cdot}001$). GH's performance was very similar to that of RS despite her lack of experience in eye movement experiments. Eighty-two of her 84 trials (98 per cent) with 3·4′ or larger target steps showed correction as did 20 of her 28 trials (71 per cent) with the 1·7′ step ($\chi^2 = 38{\cdot}6$, $df = 1$, $p < 0{\cdot}001$).[3]

The eye followed the target accurately

The eye's response to the 13·8′ step was used to calibrate responses to the smaller steps. (This procedure was validated using a sextant modified to serve as an artificial eye and also by measuring RS's response to a 28′ target step in each of the four directions.

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[3] Even if it is assumed that chance expectation was 50 per cent, because shift in average eye position was measured only on the meridian on which the target stepped, subjects' tendency to track the 1·7′ target step was reliable (RS: $\chi^2 = 4{\cdot}9$, $df = 1$, $p < 0{\cdot}05$; GH: $\chi^2 = 5{\cdot}14$, $df = 1$, $p < 0{\cdot}05$).

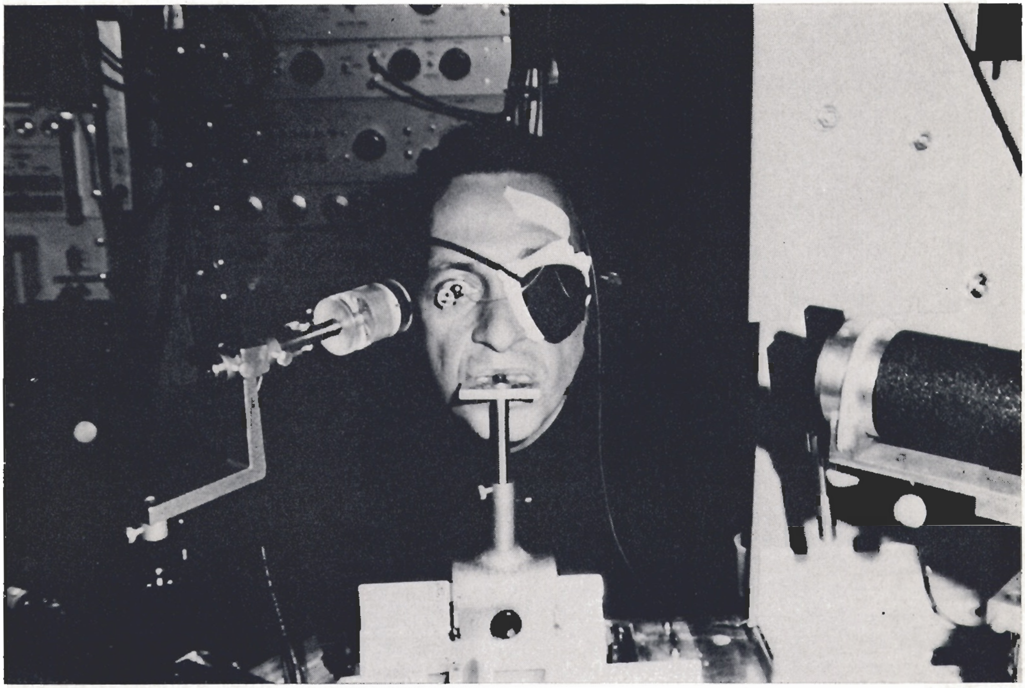

FIG. 1. Subject RS in position in the apparatus used to record horizontal and vertical eye movements, as seen from the position of the fixation target. RS's head is supported by an acrylic biteboard which holds his head rigidly in place. A narrow beam of light from the laser (seen on the right) falls on the plane first surface mirror attached to the subject's contact lens and is then reflected onto the surface of the photodetector mounted in lucite (seen on the left). The recording apparatus is seen behind the subject.

Both subjects made reasonable corrections for the 3·4 and 6·9′ target steps. Mean average changes in eye position (Δ) were within 0·5′ of the target's displacement. Correction was not as accurate when the target moved only 1·7′. Both subjects responded to this tiny target step with changes in average eye position that were too large (about 60 per cent). These results are summarized in Table 1.[4]

TABLE 1. MEAN CHANGE (MIN ARC) IN AVERAGE EYE POSITION (Δ) WHEN THE EYE MOVED IN THE DIRECTION OF THE TARGET STEP (MIN ARC) FOR SUBJECTS RS AND GH. THE NUMBER (*n*) OF TRIALS ON WHICH THE AVERAGE EYE POSITION SHIFTED IN THE DIRECTION OF THE TARGET IS ALSO SHOWN AND THE TOTAL NUMBER (*N*) OF TRIALS RUN FOR EACH STEP SIZE IS GIVEN IN PARENTHESES.

	RS		GH	
Step	*n* (*N*)	Δ (S.D.)	*n* (*N*)	Δ (S.D.)
1·7	27 (40)	2·8 (1·2)	20 (28)	2·6 (1·4)
3·4	40 (40)	3·8 (1·7)	26 (28)	3·8 (1·5)
6·9	39 (40)	7·4 (2·7)	28 (28)	7·0 (2·4)

The eye mainly used saccades to correct for target steps

The pattern of the oculomotor response to small target steps was examined qualitatively. Both subjects (particularly GH) used a variety of idiosyncratic saccadic response patterns to correct for target displacements. Figure 2 shows copies of 2 of GH's typical *Visicorder* records.

The bottom record shows GH's response to a 13·8′ step to the right. About 300 msec after the target step, she made a single saccade to the right and then fixated at the new position. The top record shows her frequent response to a left target step of the same size. About 100 msec after the target step, she began a series of five small saccades which brought her eye to its new steady-state position within 1 sec. The vertical eye movement traces in the two higher speed records shown in Fig. 3 are typical of GH's eye movement pattern on the vertical meridian. Both records show that she maintains vertical position almost exclusively with slow control (drift correction). Saccades rarely occur during maintained fixation on this meridian. However, despite her predominance of slow control on the vertical, GH did respond to vertical target steps with saccades as can be seen in the bottom record. Figure 4 shows similar response patterns used to correct for the smaller target steps. Note that all the corrective patterns were primarily saccadic.[5]

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[4] It has been suggested to the authors that subjects make a measurable eye movement response to an audible click and that this might have contaminated the measures of accuracy reported in Table 1. Indeed, WYMAN (1972) found in a subsequent series of experiments which dealt with characteristics of the first tracking saccade after a target step that the simultaneous occurrence of an auditory with a visual signal (the target step itself) produced first tracking saccades that were slightly larger (about 14 per cent) than those obtained when only the target step told the subject when to respond. However, the accuracy measures reported in Table 1 would not be affected, because they reflect the steady-state shift in eye position produced by the target step, excluding the 1·5 sec period immediately following the target step during which the first tracking saccade occurred.

[5] A number of records were made after instructing the subjects to suppress saccades completely throughout the trial. Both subjects were able to do this, and very little correction for any but the smallest target steps was observed. We doubt that the slow control system can be activated by target steps much larger than 7′ but we do not have sufficient data at this time to support this speculation.

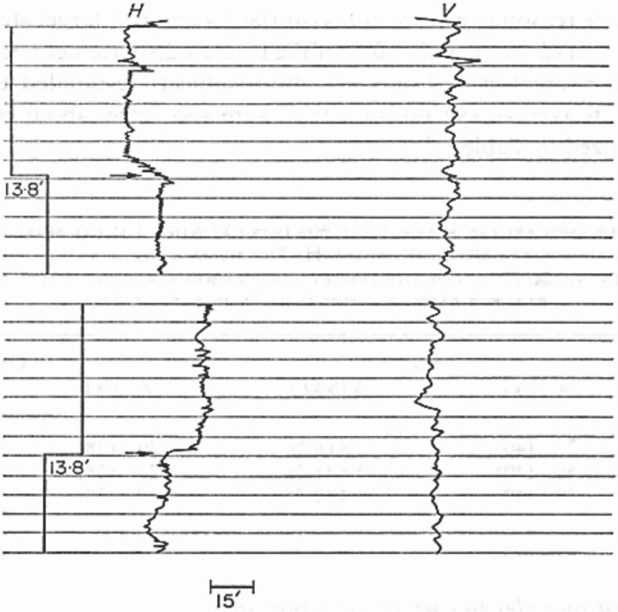

FIG. 2. Two typical 2-dimensional recordings of GH's eye movement response to visual errors introduced by displacing the fixation target (recording speed = 0·5 cm/sec). A trial begins at the bottom of each record. Digital indications of eye position appear on the left. The first trace on the left is an event marker showing the time of onset and approximate magnitude of horizontal target steps. The second trace (H) shows the horizontal component of her eye movements. The vertical component is shown in the next trace (V). The last trace, on the right, is an event marker signalling vertical target steps. The arrows indicate when the step occurred. The repetitive horizontal lines are a 1 sec time base. The horizontal bracket at the bottom indicates the extent of a 15′ change in eye position in the analog traces. Both of these records show GH's response to 13·8′ horizontal target displacements.

DISCUSSION

The term "dead zone" is widely used in engineering to describe a region of stimulus strengths (usually near zero strength) to which a system does not respond. Thus, the oculomotor system would be said to have a "dead zone" if it failed to respond to displacements of a fixation target smaller than some threshold size [e.g. the 0·25–0·5° threshold reported by RASHBASS (1961)].

Considerable confusion exists in the literature about the logical and physiological significance of such a "dead zone". In this regard, it is useful to conceive of the oculomotor system as three subsystems acting in series: the sensory, processing and motor control subsystems. If the eye failed to respond to a small step displacement of the fixation target, the failure would be a consequence of some limitation in one of the subsystems. For example, the step may be below the sensory subsystem threshold, so that no signal is passed on to the processor, and the information that the step has occurred is lost to the oculomotor system. Alternatively, the sensory subsystem may transmit the information that the target was displaced, but the processor may fail to transmit it to the motor control subsystem, possibly because of its instructions or construction. Thus, the presence of a "dead zone" may be a result of properties of either the sensory or processing subsystems.

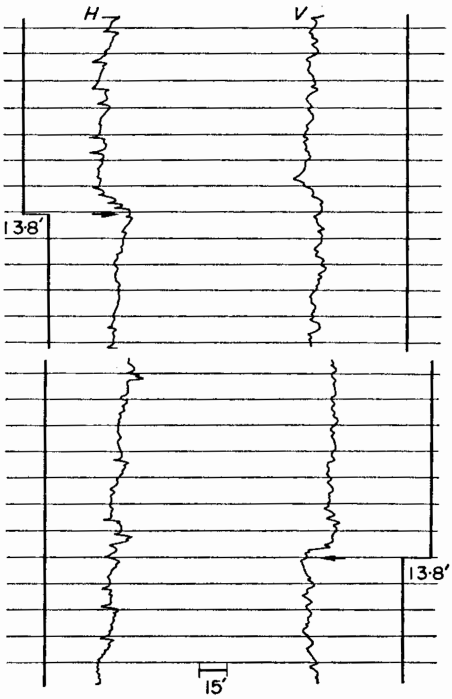

FIG. 3. High speed (1 cm/sec) 2-dimensional eye movement recordings of GH's response to large displacements of the fixation target. The top records shows GH's reponse to a 13·8′ target step to the left. The bottom record shows her response to a 13·8′ downward target step.

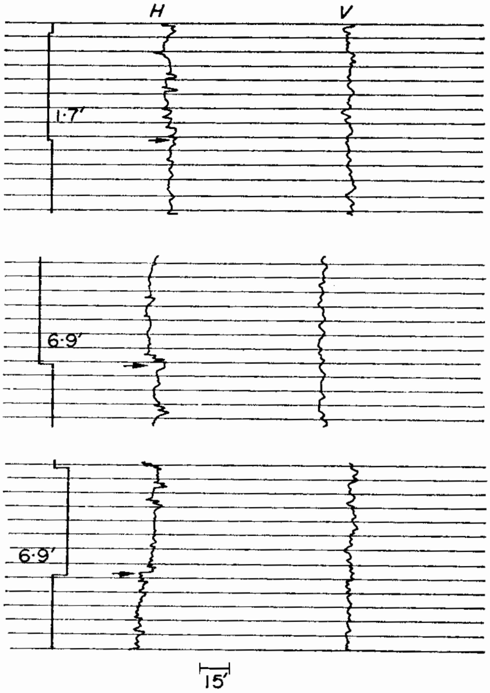

FIG. 4. Three representative 2-dimensional eye-movement recordings of GH's response to small displacements of the fixation target (recording speed = 0·5 cm/sec). The top record shows GH's response to a 1·7′ displacement of the fixation target to the left. The other two records show her response to horizontal steps of 6·9′.

It appears, superficially, that a "dead zone" could also be a consequence of properties of the motor control system. However, this is not the case: the argument is that a "dead zone" would result if the system were unable to generate a saccade smaller than some threshold size (e.g. 15′). But such a motor control limitation would not produce a "dead zone" or a range of target step sizes to which the oculomotor system could not respond. Rather, such a limitation would produce responses of inappropriate size. These responses would occur unless the processor were instructed to inhibit inappropriate responses, in which case the "dead zone" would be a manifestation of properties of the processor—not of the motor control subsystem. Consequently, an oculomotor "dead zone" could only result from some limitation in the sensory or processing subsystems.

In the present experiment, we have shown that subjects consistently (98 per cent of the time or more) and accurately (to within 0·5′) correct for target displacements of 3·4, 6·9, and 13·8′. Further, the oculomotor system uses primarily saccades to correct for the very small visual errors produced by these target steps. The findings demonstrate clearly that the error signals generated by these small step displacements of the fixation target are not lost to the sensory subsystem but are received and then transmitted to the processor, which, in turn, commands the motor control subsystem to make a corrective response. N.B. the correction of very small target step displacements does not require practice and is not dependent upon the prior experience of the subject. The performance of the completely inexperienced subject, without any prior practice, was very similar to that of the highly experienced and practiced eye movement subject.

The fact that 1·7′ target steps were likely (65 per cent) to be followed suggests that the input provided by even this tiny target step is not lost to the oculomotor system. Further, although it is true that subjects very rarely can make saccades as small as 2′, this motor limitation has little significance for small step tracking because, with an appropriate combination of saccades and drifts, the subject is able to bring his line of regard closer and closer to the center of the target, so that after a few seconds his eye is centered once again even though the target has moved by an amount smaller than the smallest voluntary saccade. This is illustrated in the top record in Figure 4 where GH is using such a pattern to correct for a 1·7′ target step to the left and the change in average eye position was 2·1′.

It is difficult to understand how RASHBASS (1961) could have found the large saccadic "dead zone" which he reports. Perhaps, if he failed to instruct his subjects to correct for all changes in target position, they may simply have chosen to ignore the small visual errors produced by target steps smaller than 0·25°. In this case, the processor would be under instructions not to program a corrective movement for stimulus-produced visual errors of less than 0·25° and a "dead zone" would result. Alternatively, it is possible that some stimulus feature, such as the color of the fixation target, could be responsible for the discrepancy between the Rashbass findings and our own. (Rashbass' subjects tracked a blue target of unspecified luminance, while our subjects tracked a green target 1·6 log units above absolute foveal threshold.) We doubt this interpretation, however, because target characteristics have only modest effects on the fixation pattern once the target is photopically effective (STEINMAN, 1965).

In conclusion, Rashbass reported a threshold target displacement of 15–30′, but we have shown that the threshold is certainly smaller than 3·4′ and probably smaller than 1·7′. Consequently, the apparent contradiction between the sensitivity of the oculomotor system to small errors during maintained fixation of a stationary target and its insensitivity to much larger errors during small step tracking is not a real one: the saccadic control system seems to make no distinction between intrinsic fixation errors (produced by the oculomotor system itself) and extrinsic fixation errors (produced by sudden displacements of the fixation target). The subject makes small corrective saccades, regardless of how the fixation error is produced. This result simplifies the task of understanding oculomotor control because we need not figure out why experimentally produced visual errors would be less effective than errors produced by the subject's own eye movements.

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Abstract—The apparent contradiction between the sensitivity of the oculomotor system to small errors during maintained fixation of a stationary target and its insensitivity to much larger errors during small step tracking reported by RASHBASS (1961) was resolved in this paper by using the contact lens optical lever technique to study the manner in which the oculomotor system responds to small step displacements of the fixation target. Subjects did, without prior practice, use saccades to correct step displacements of the fixation target just as they correct small position errors during maintained fixation: they consistently (>98 per cent) and accurately (to within 0·5′) tracked target steps ranging from 3·4 to 13·8′.

Résumé—On résoud dans ce travail l'apparent contradiction signalée par RASHBASS (1961) entre la sensibilité du système oculomoteur à de petites erreurs durant une fixation soutenue sur une cible stable et son insensibilité à de beaucoup plus grandes erreurs durant une poursuite à petits échelons. Pour celà on emploie une technique de levier optique par verre de contact afin d'étudier de quelle manière le système oculomoteur répond à de petits déplacements en échelons de la cible de fixation. Sans entrainement antérieur, les sujets emploient des saccades pour corriger le déplacement en échelons de la cible de fixation exactement comme ils corrigent de petites erreurs de position durant la fixation maintenue: avec régularité (>98 pour cent) et précision (à mieux que 0,5′) ils suivent des échelons de la cible compris entre 3,4 et 13,8′.

Zusammenfassung—Der suffällige Widerspruch zwischen der Empfindlichkeit des okulomotorischen Systems gegenüber kleinen Fehlern während anhaltender Fixation einer stationären Marke und seiner Unempfindlichkeit gegenüber viel grösseren Fehlern für Folgebewegungen in kleinen Schritten, wie VON RASHBASS (1961) berichtet, wurde in dieser Arbeit aufgelöst, indem die Kontaktlinsen-Technik zum Studium der Art und Weise, in der das okulomotorische System auf kleine schrittweise Verschiebung der Fixiermarke reagiert, benutzt wurde. Die Versuchspersonen benutzten ohne vorheriges Training Sakkaden zur Korrektur von schrittweisen Verschiebungen der Fixiermarke in derselben Weise, wie sie kleine Positionsfehler während anhaltender Fixation korrigierten: sie verfolgten konsistent (>98%) und genau (innerhalb von 0,5 Winkelminuten) die Schritte der Marke im Bereich von 3,4 bis 13,8 Winkelminuten.

Резюме—Кажущееся противоречие между чувствительностью глазодвигательной системы к небольшим ошибкам во время постоянной фиксации стационарного объекта и ее нечувствительностью ко много более значительным ошибкам во время небольшого по амплитуде скачкообразного прослеживания объекта, разрешено в этой работе с помощью метода контактной линзы со специальной оптической системой (contact lens optique lever technique), для изучения способа каким глазодвигательная система отвечает на небольшие скачкообразные смещения фиксируемого объекта. Испытуемые, без предварительных упражнений, используют саккадические движения для коррекции скачкообразных смещений фиксируемого объекта, так же как они коррегируют небольшие ошибки положения во время постоянной фиксации: они постоянно (>98%) и точно (в пределах 0,5 дуговых минут) прослеживают за скачкообразными смещениями объекта в пределах от 3,4 до 13,8 угловых минут.