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Types of Gaze Movement: Variable Interactions of Eye and Head Movements

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The patterns of coordinated eye-head movement in gaze shift are influenced by preconditions of the experimental protocol, such as the predictability and amplitude of the stimulus and the subject's endeavor to move as instructed, either naturally or as fast as possible. Gaze-shift movements fall into four distinct types with respect to eye-head latency, each one involving particular gaze-shift errors and head acceleration trajectories.

INTRODUCTION

A gaze shift is a movement of the fovea in space as a result of coordinated head and eye movements responding synkinetically to a target jump. Although the neurological controller signals—represented by the envelope of the electromyogram (EMG)—arrive simultaneously, the eye movement saccade is begun and completed before the head makes any significant movement (5, 30, 32). Eye rotation is much faster because the eyeball requires only a simple viscoelastic effort of the very quick extraocular muscles; head rotation lags because the head provides a large viscoinertial load for the comparatively slow-moving skeletal neck muscles (8, 24, 29, 31). While the head is continuing to rotate through its longer trajectory after the eye saccade has found the target, the vestibular ocular reflex

Abbreviations: EMG—electromyogram, VOR—vestibular ocular reflex, CEM—compensatory eye movement, EOG—electrooculogram.

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(VOR) and other components of compensatory eye movement (CEM) rotate the eye at an equal rate in the opposite direction. Thus, the eye is able to remain fixed on the target while head rotation is substituted for orbital eye rotation, and to be in primary (gaze) position at the end of the coordinated movement.

The features of normal coordinated gaze shift have been defined in monkeys (5, 6, 10, 18, 21, 22) and in human beings (1–4, 11, 13, 14), and some abnormalities have been described in clinical studies (1, 12, 15, 17, 20, 23, 32–34). These data have been supplemented by quantitative modeling (8, 31, 32). Under experimental conditions, the latencies of the head and eye components of gaze shift have been shown to be affected by several interacting factors, including predictive anticipation of the target jump, the amplitude of the target jump, and the vigilance of the subject (5, 7, 11–14, 19, 23, 26, 28, 30, 32). This report describes and analyzes the phenomena involved in gaze shift and provides a basis for (i) distinguishing a few basic types among the complex sets of gaze-shift patterns and (ii) understanding the conditions that give rise to each type.

METHODS

Recording of Eye and Head Movements. The techniques used in our laboratory for recording eye and head movement were reported (29). In brief, mechanical linkages and potentiometers are attached to a bicycle helmet worn by the subjects while viewing the targets. Residual play between the helmet and the head produces a latency of 30 ms as determined by calibration with a photocell mounted on the head. In the results reported below, this latency has been taken into account and subtracted.

Eye movements were recorded either by the infrared limbus-reflection technique (26) or (for large amplitudes such as combined eye–head movements of 30 or 60°) with monocular electrooculogram (EOG) (Beckman miniature electrodes). The electromyogram (EMG) measurements were made with surface electrodes situated over pairs of neck muscles (such as the splenius and sternocleidomastoideus) that are involved in horizontal rotation of the head (29, 30). The target appeared as a bright, continuously lighted spot of 30 arc min that was projected onto a dark screen.

Programs. Stimulus programs included both predictable and unpredictable sequences of target steps. Predictable target jumps with amplitudes of 15, 30, 40, and 60° shifted with frequencies randomly varying between 0.1 and 1.9 Hz. Unpredictable target shifts varied randomly in amplitude between 6 and 60° and in frequencies between 0.1 and 1.9 Hz. Random amplitudes and frequencies were generated by a digital computer (PDP-8) using a random number generator.

Subjects were seated comfortably in front of the screen and, for the first run, were advised to engage in "natural" head and eye movements. For the second run, they were instructed to force themselves to perform head and eye movements as rapidly and accurately as possible (intended time-optimal) (8, 30, 32). Recordings were made of these movements performed by four naive subjects and by three of the investigators.

Analysis of Data. At least 35 samples of each stimulus condition were obtained for analysis. Data were recorded on a rectilinear chart recorder, from which they could be fed into the PDP-8 laboratory minicomputer system (29).

Data were analyzed by standard statistical techniques, including Student's *t* test and linear regression analysis (9).

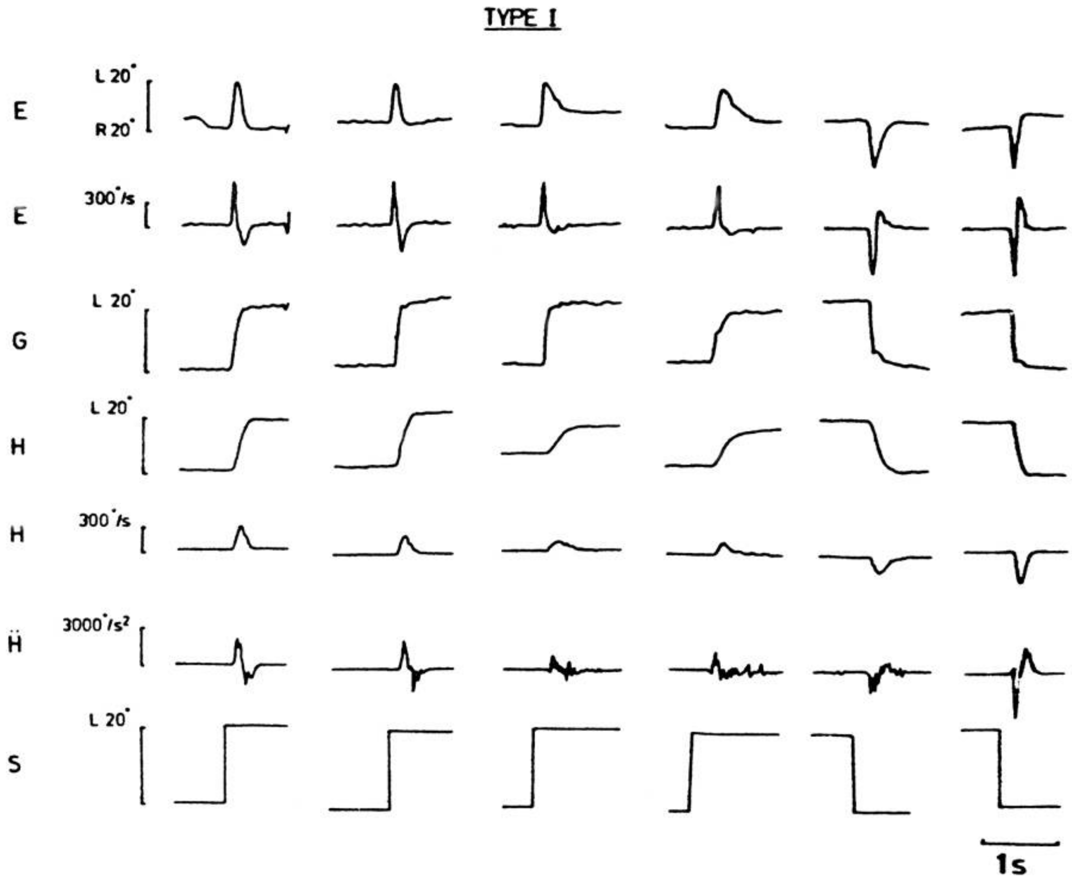

FIG. 1. Type I gaze shift. Note the variability of the head and eye movements that result in a Type I gaze-shift movement. Abbreviations in this and the following four figures are the same: E—eye position; Ė—eye velocity; G—gaze position, that is eye position plus head position; Ḣ—head velocity; Ḧ—head acceleration; S—stimulus position. Upward represents left; downward, right. The inflection lines below the traces are time calibrations indicating 1 s. Calibrations are: positions 40°, velocities 300°/s, acceleration 3000°/s^2.

RESULTS

Separate analyses of the velocity and acceleration components of gaze shift demonstrated the dynamics of both eye and head movements more sensitively than analysis of the combined eye–head movements that comprise gaze shift, because these components are more directly related to the actual changes in muscle force. This analysis revealed four distinct types of gaze-shift movements.

Type I. Synchronous Eye- and Head-Controller Signals

When the EMG indicated that neurologic controller signals to the eye and the neck muscles were synchronous, the gaze-shift pattern (Type I) consisted of a rapid eye saccade that attained the new gaze position before the head moved significantly (Fig. 1) and then held that position while head movement was substituted for eye movement. Type I gaze shifts showed considerable variability. This was due both to varying CEM velocities and to varying acceleration of head movements in response to controller signal variables. The CEM components of Type I gaze shift were often modified by quick-phase interruptions. Overall, Type I occurred 34% of the time in our subjects. It has also been found to occur frequently in studies of monkeys (5, 6). In our study, its frequency relative to other gaze shift types (Table 1) was affected by various conditions governed by the protocol. Type I occurred more frequently when target brightness was high or when the subject's vigilance was low, whereas its occurrence was comparatively unaffected by changes in the amplitude or predictability of target presentation or the subject's endeavor to be time-optimal.

Type II. Late Head Movements

Delay in the head-movement component produced an interval following the completion of the eye saccade when either the gaze remained stationary or the initial component of the CEM occurred before the head movement began, producing anticipatory CEM (Fig. 2). This anticipatory CEM occurred more frequently and was increased in amplitude and velocity when the amplitude of the gaze shift was small and head acceleration was low. The velocity of the head movements generated as a result of the CEM often equalled the velocity of the initial anticipatory CEM.

The overall frequency of Type II gaze shift was comparatively low. This pattern of delayed head movement is common in patients with occipital hemianopia (20, 32, 33), but it is rare in normal subjects (11).

Type III. Early Head Movement

An early head movement resulted in superimposition of the saccadic eye movement upon the ongoing head trajectory with its concurrent VOR. This

TABLE 1

Influences Affecting the Relative Frequency of the Major Types of Gaze Shift

Gaze type	Average percent of occurrence	Test condition (ratio of frequency)					
		Amplitude small/large	Intent forced/natural	Predictability high/low	Vigilance high/low	Target brightness high/low	Helmet pointer with/without
Type I	34	0.90	0.73	0.71	0.65	1.88	1.04
Type II	4	0.09	3.80	0.75	5.90	1.31	0.55
Type III	43	3.05	2.20	1.60	1.33	0.72	1.27
Type IV	19	2.10	3.50	2.90	0.97	0.60	1.11

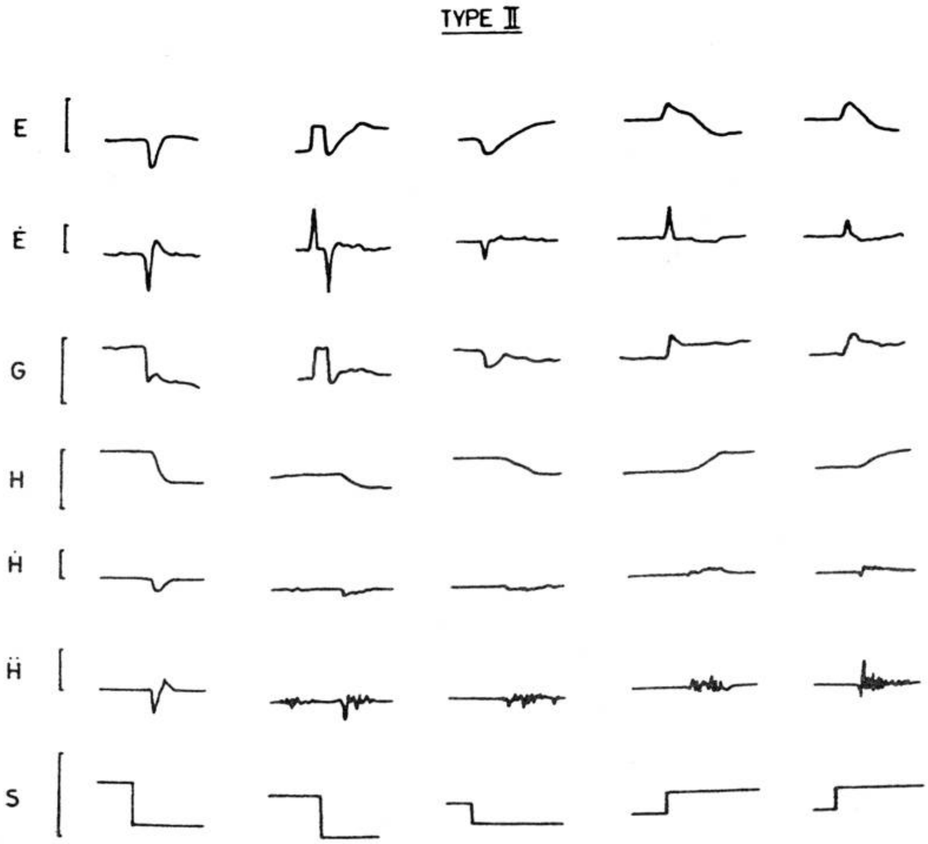

FIG. 2. Type II gaze shift. Note the anticipatory compensatory eye movement that brings the eye off target before the head has started to move. This is best seen in the gaze trace. Abbreviations as in Fig. 1.

interaction resulted in an initial eye velocity in opposition to the eye saccade.

Type III occurred 43% of the time in normal subjects. Its occurrence was more frequent in gaze shifts of large amplitude, where the head movement assumed increased importance because eye saccades were normally 15° or less in amplitude. Other protocol conditions conducive to the occurrence of Type III were readily predictable target jumps and effort by the subject to force rapid target acquisition.

A subtype (Type IIIA) was distinguished by truncation of the eye saccade (Fig. 3) and of course an abnormal and truncated gaze movement. Compare the truncated gaze step responses of Type IIIA (Fig. 3) with the full gaze step responses of Type I (Fig. 1). The resulting error—gaze falling short of the target—was compensated for by either a corrective eye saccade occurring at the conclusion of the head movement, or a diminished CEM gain that allowed the eye to reach the target gradually.

Another distinct subtype (IIIB) was distinguished by the late appearance

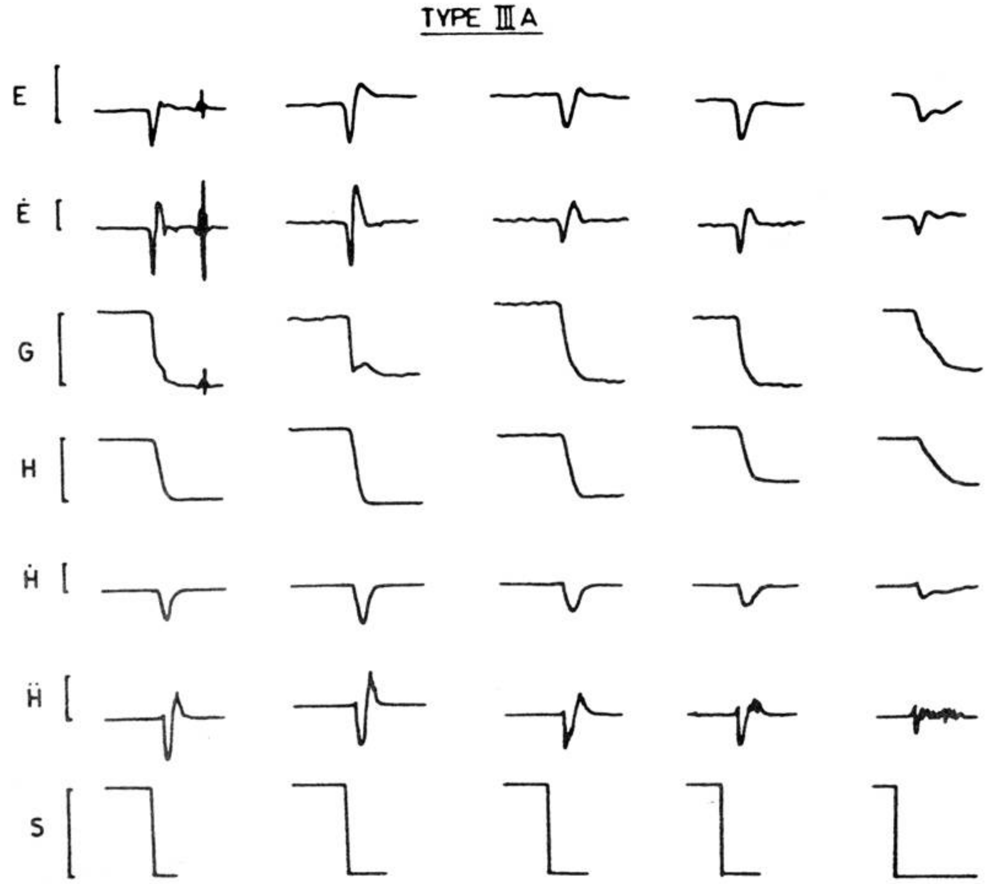

FIG. 3. Type IIIA gaze shift. Note the considerable slowing and truncation of the eye saccades, particularly in the three traces on the right. Abbreviations as in Fig. 1.

of the eye saccade, causing it to interact with the by then well advanced CEM (Fig. 4). Occasionally, this resulted in the occurrence of several saccades producing a pattern quite similar to the quick phases seen in patients with vestibular nystagmus.

Type IV. Early Head Movement with a Final Independent Eye Saccade

Sometimes an eye saccade began so late that the head movement was already completed, or nearly so (Fig. 5). In this type of gaze shift, the VOR ongoing concurrently with the head trajectory was also completed before the eye saccade began, allowing scant opportunity for synchronous coordination. With Type IV gaze shifts, eye saccades were variable and sometimes so delayed that the gaze remained off target for a comparatively long time. This resulted in head movements that preceded the gaze shifts (Fig. 5), rather than gaze shifts that occurred during head movements in Type IIIB (Fig. 4) and different still from Type I gaze shifts that preceded head movements (Fig. 1). Thus, the early head movement did not afford

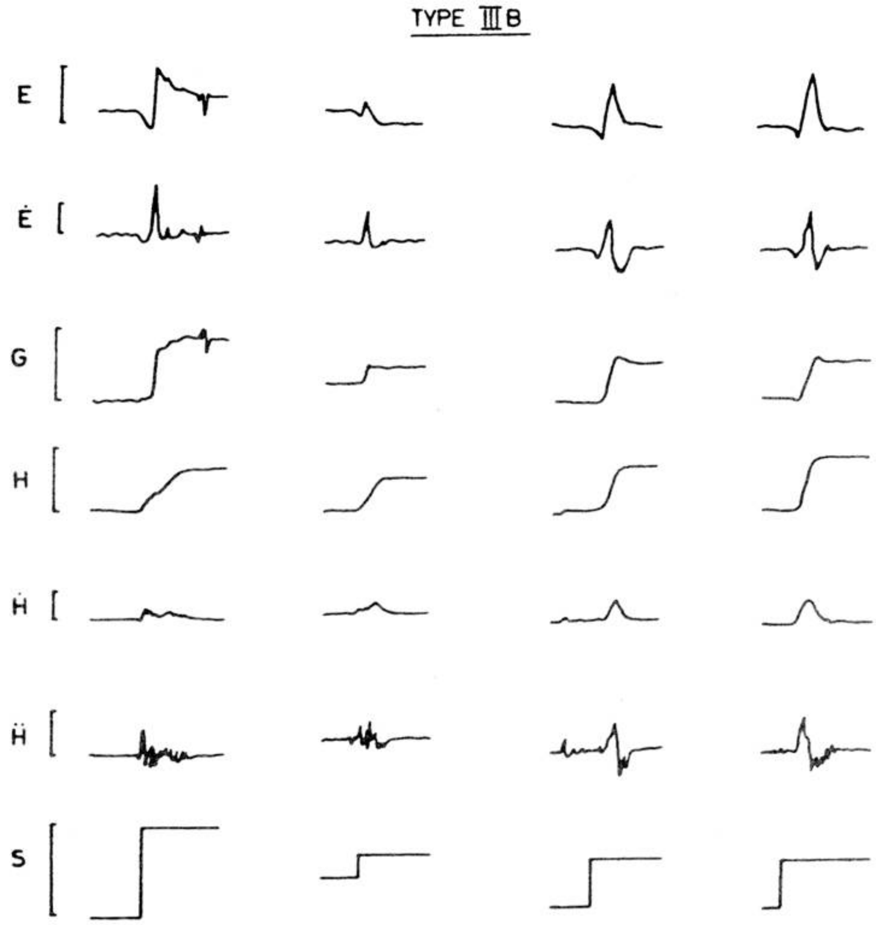

FIG. 4. Type IIIB gaze shift. Note that the eye starts with a compensatory eye movement, and only after this is partly executed does a slow saccade occur. Abbreviations as in Fig. 1.

early acquisition of the target in this gaze shift type as it did in Types I and II.

Factors conducive to Type IV gaze shift were target movements of large amplitude, endeavor by the subject to shift gaze as rapidly as possible, and low target brightness (Table 1).

DISCUSSION

The Gaze Plane

The relative latencies of eye and head movement that serve to define the four types of gaze shift can be depicted in the gaze plane, which is an abstraction of the gaze trajectory in terms of its components, the eye trajectory and the head trajectory (Fig. 6A, B). In this graphic model, the eye and head components of gaze shift are depicted as functions of one another, with time regarded as only an implicit function of eye and head position.

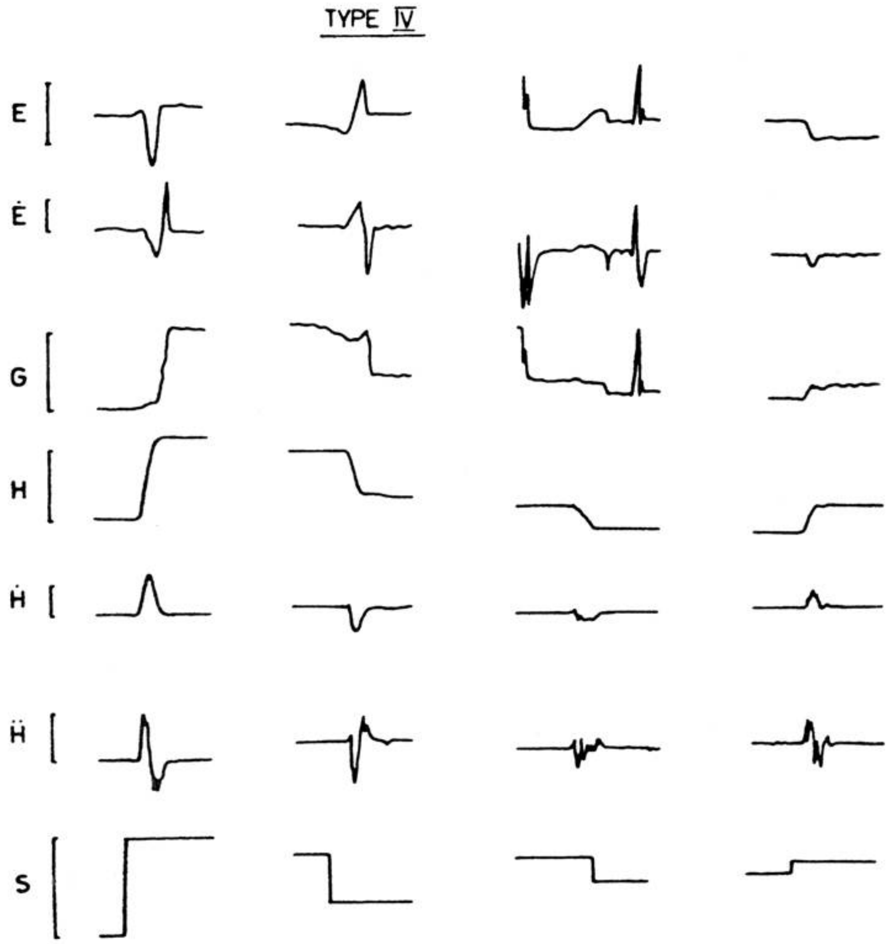

FIG. 5. **Type IV gaze shift. Note that the eye starts with a compensatory movement that is completed before the eye saccade finally occurs. Abbreviations as in Fig. 1.**

For example, in the gaze plane for Type I (Fig. 6A), the fast eye saccade that occurs first is represented by the vertical arrow from the origin; the subsequent head movement and simultaneous CEM combine to keep the gaze (i.e., eye in space, represented by the diagonally downward solid arrow) fixed on target throughout the gaze shift—provided that the CEM gain is equal to unity. A CEM gain that is higher or lower (dashed arrows) will move the gaze slightly off target during the head trajectory (compare the representation of nonunity CEM represented as a time function in the eye and head trajectories of the gaze trajectory). Normally, nonunity CEM gain will not severely affect the efficiency of target acquisition because the postsaccadic "snapshot" has already been obtained and the gaze can be returned to exactly on fovea by means of corrective saccades.

Correction of Errors

Error—that is the difference between target angle and gaze angle—is an important factor in gaze-shift patterns because both eye and head move-

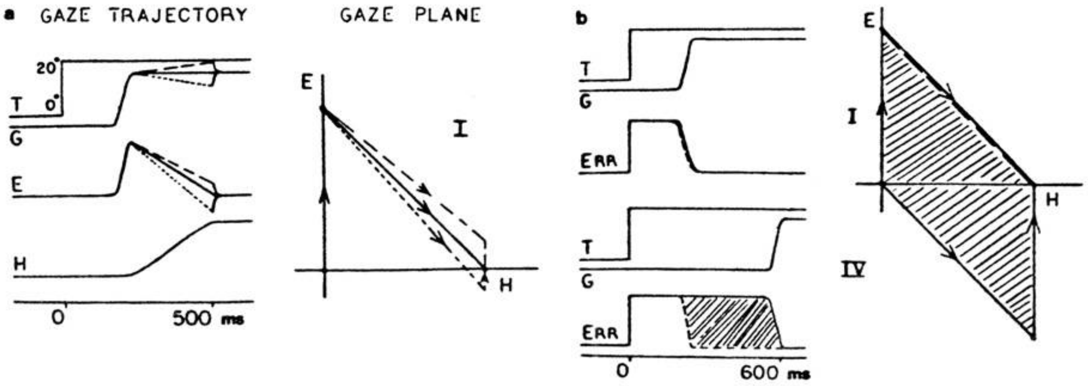

FIG. 6a. Type I gaze shift. Depiction of gaze shift as the gaze trajectory (left): gaze shift movement (G) in response to the target movement (T) is the sum of eye movement (E) and head movement (H). Compensatory eye movement (CEM), which is the ratio of eye to head velocity, is represented by the dashed lines—low CEM gain by the long-dash and high gain by the short-dash line. Abscissa: time in ms; ordinate: amplitude in degrees. Depiction of gaze shift in the gaze plane (right), where time is only an implicit function: eye movement is represented by the vertical arrow beginning at the origin. The replacement of eye amplitude by head amplitude (head movement and CEM), is represented by the diagonally downward arrow that ends at the final head position (20° left) and eye position (0°); here too, CEM gain is indicated by the dashed lines. FIG. 6b. The significance of the different types of gaze-shift errors represented in the gaze trajectory (left) and the gaze plane (right). In the gaze trajectory, gaze shift in response to an unpredictable target movement shows two sorts of errors: the typical error is represented by the narrow space between the dashed line and the gaze trajectory (upper left) that is caused by the latency of the eye, which is 200 to 250 ms; and excess error (lower left) is represented by the cross-hatched area. The extent of excess error depends on the type of gaze movement that is utilized: the excess error is zero for Type I gaze shift (lower trace). In Type IV head movement, the total error amounts to 600 ms because duration is subjoined to a head latency of about 250 ms, and gaze movement is finished only after the final eye saccade has completed. The extent of excess error that occurs in Type IV gaze shift is represented by the cross-hatched area. Compare the excess error of Type I gaze shift represented in Fig. 6a.

ments are error actuated by visual feedback and, therefore, continuously monitored by the subject.

In Type I gaze shifts, error is the variable that is crucial to efficiency, for it persists only during the short eye latency period and the very rapid eye saccade (Fig. 6B). In Type IV on the other hand, where the gaze shift response is made without predicting the target location, it takes much longer for the fovea to acquire the target because the head movement trajectory is completed before the eye begins its saccadic trajectory (Fig. 6B). A large error persists for approximately 600 ms, including 250 ms of latency of the head movement, 300 ms employed in the long head trajectory, and 50 ms used for the subsequent eye saccade.

The extent of "excess" error involved in the various types of gaze shift is represented by the cross-hatched areas in the gaze trajectories and gaze planes of the respective types arrayed in Fig. 7. It is immediately apparent both from the gaze planes and from the time functions represented in the gaze trajectories that Type I minimizes gaze-shift error and is the most time efficient.

Gaze Types

The basic patterns and the variability of the four types of gaze shift are illustrated in the sample traces presented in Figs. 1 through 5. When the gaze-shift types are represented in the gaze plane (Figs. 6A, B and 7), their motor coordination features can be abstracted for analysis.

Type I. Because the error in Type I gaze shift is due solely to eye latency, there is normally no excess error. Variations in head acceleration may, however, result in excess error due to too much or too little CEM gain or to quick-phaselike saccades.

Type II. The delayed head movement and early target acquisition char-

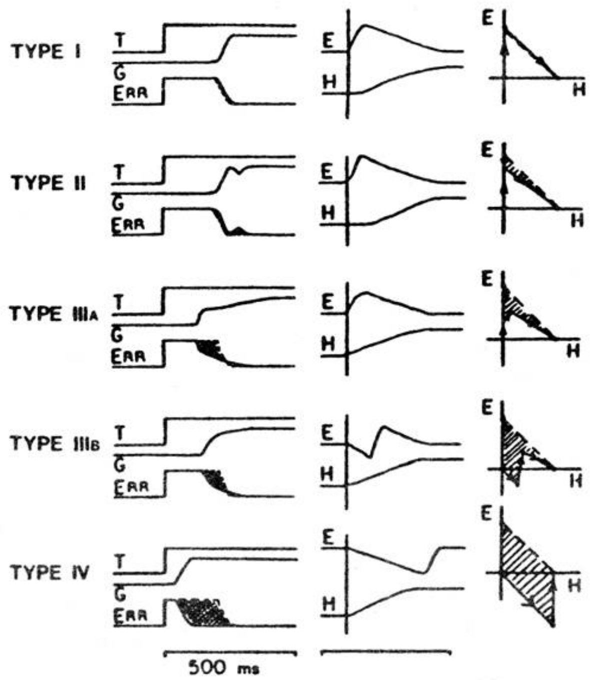

FIG. 7. Typical examples of the major gaze shift types with the extent of excess error depicted by the cross-hatched areas, represented as time functions in the gaze trajectory (left column), and in the gaze plane diagrams (right column). In the middle column, eye and head time functions are represented with the vertical line indicating the extent of eye latency in relation to head latency, which depends on the extent of anticipatory prediction involved in the particular gaze shift type. Note that with increasing predictive anticipation of the head movement there is a negative excess error (left column). By eliminating the time function, the gaze plane diagram better indicates the actual extent of excess error that a particular gaze type involves.

acteristic of Type II typically result in an anticipatory CEM that does not compensate for the VOR but, rather, moves the gaze off target. The excess error shows up after the initial acquisition of the target. With slow head velocities, there are often low-gain CEMs that make corrective saccades unnecessary.

Type III. The early head movement in Type III is not actually due to delay of the eye saccade, but to early movement of the head, which is more flexible in response to prediction of the target location. With predictable targets, the excess error in gaze shifts of Type III is often much diminished. When the target location is correctly predicted with sufficient promptness, the "excess error" may actually be negative, as in Types IIIA, IIIB, and IV (Fig. 7). The minimization of error achieved by accurate prediction of the target location is not represented in the gaze plane as time is not directly depicted. Instead, the cross-hatched areas in the gaze planes represent the potential extent of excess error if the target location is not correctly predicted.

Head movement often occurs so early, in relation to the initiation of the saccadic eye movements, that resultant dynamic interactions become significant. Type IIIA represents a saccade that occurs early in the head trajectory and is slowed down and truncated by the VOR. When the eye saccade occurs later in the head trajectory, as in Type IIIB, it may be even further slowed and truncated as a result of interaction with the peak head acceleration and maximum VOR activity.

Truncation of the saccades in such cases may be due to interactions of neuromuscular forces and peripheral biomechanical actions as the opposite pull of the VOR reduces the force of the muscles generating the saccade (8, 31). Alternatively, the truncation may be due to control signals of the central nervous system interacting at the level of the brain stem (21). Truncation is often compensated for by diminished CEM gain, which may, in turn, be due either to altered control signals from the central nervous system or else to the biomechanical effects of a saccadic movement on the ongoing VOR. The saccades in Type IIIB look very much like the quick phases seen in nystagmus, and this may indicate that this type of gaze shift is somehow related to the generation of vestibular nystagmus. In most gaze-shift types there are a number of small saccades that intrude upon the smooth VOR (except Type IV, where the eye saccade occurs too late to interfere with the VOR); similar small saccades also occur in vestibular nystagmus as fragments with fast phases.

Type IV. The extreme delay in the eye saccade in Type IV can result in very extensive excess error if the movement of the target is incorrectly predicted. This excess error shows up both in the gaze plane and in the time functions depicted in the gaze trajectory. The gaze plane represents the extent of excess error that is possible if the target location is incorrectly predicted. Negative excess error occurs when the correct target location is predicted almost immediately and the head movement consequently occurs so early that the eye saccade, though very delayed, still occurs before the initial eye saccade in Type I.

Neurology of Gaze Shift Types

One important factor in the generation of the various gaze shift types is the extent to which head movement latency is affected by prediction of the target location. Because head movement latency is much more variable than eye movement latency, the range of gaze shift types correlates with the latency of the head movement component, ranging in scope from the delayed head movement of Type II to the very early head movement of Type IV. The speed with which head movement responds to predictions of the central nervous system is almost as great as that of arm movements (24, 25).

Another important factor in the generation of gaze-shift types is the variability in head-movement acceleration. The patterns of head-movement acceleration have been studied both in experimentally induced dynamic responses and in model simulations of head movement (29–32). In Type II, the head movements tend to be of small amplitude and to have slow, fragmented acceleration trajectories. In Types III and IV the early head movements are associated with larger amplitudes and faster acceleration trajectories; and the positive acceleration peaks are generally greater than the negative peaks and less fragmented. Our EMG experiments (30) demonstrated that predictive head movements of large amplitude that are very prompt are generated by fast, highly efficient controller signals. In Type I gaze shift, the head movements are associated with head accelerations that—by contrast with the rather stereotyped eye acceleration trajectory—are highly variable.

Thus, the differentiation of gaze shift types and their variants is mainly determined by the great flexibility of head movements that results from the influences of several levels of the central nervous system: prediction and intention derive from the higher levels, and the lower levels are responsible for the variation in dynamic trajectories and the interaction of the VOR and eye saccades.

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