A classical problem in understanding the control of movement in natural environments is the question of how different motor activities—movements of the eyes, head, and arms, for example—are linked in space and in time to create effective and well-coordinated patterns of action. Perhaps the most compelling modern statement of this problem was made by Lasley (1951), who was seeking what he called "a syntax of movement," which he defined as "an habitual order or mode of relating the expressive elements...which may be imposed upon a wide range and a wide variety of specific acts." (p. 122). Lasley rejected the idea that individual movements were triggered by isolated sensory signals because, he believed, could not account for the elegant and apparently effortless patterns of action found in such activities as the coordinated leg movements of insects or the trotting and posting of a horse. Lasley argued that the key to the achievement of coordinated patterns of action was to program diverse motor responses with reference to a single, central spatial map and a single internal clock. This chapter, inspired by Lasley's ideas, examines the coordinated movements of the head and the eyes during the performance of natural, and some unnatural, visual tasks.

Lasley's ideas have led many researchers in human movement control to try to describe and to model the spatial and temporal coordination of action sequences. Consider a few relatively recent examples:

1. Vivanti and Terzolo (1980) described consistent spatial and temporal relationships in handwriting that remained constant despite changes in the size of the written characters or the speed of writing.

2. Steinberg et al. (1978a, 1978b) found that the latency to begin a sequence of spoken syllables or typed keystrokes, and the time between successive responses in the sequence, depended on the number of elements in the sequence. The effects were greater for motor programs that were defined in a search model, in which programs for all the movements of the sequence were created in advance of each movement. The findings are consistent with the idea that individual programs are prepared at the beginning of a sequence, and retrieved when needed during the execution of the sequence. As Stevens et al. (1969) suggested for typing and speech, Zingale and Kohler (1987) suggested that the preprogrammed saccadic sequences are useful because they facilitate the coordination of saccadic and pursuit movements, and that the pursuit movements, and the idea in keeping with Lasley's notion of a shared internal clock used to ensure the proper temporal concomitance of concurrent motor activities. An incidental observation supported this view. Zingale and Kohler asked one of their subjects to try to look from one target point to the next as rapidly as possible. The experiment, like the rest of their experiments, was done with the head stabilized by a bite block because of limitations of the eye movement recording equipment (Kehn, Purkinje Image Trackers). Under the instruction to scan as quickly as possible, interocular differences in speed reduced and saccadic accuracy was poorer as would be expected. What was not expected was the strong discomfort in the neck muscles, a subject felt, as she was scanning to continue to do the task while keeping her head from flying off the bite block. It was at the internal instruction to "make a saccade to each target point" was, in fact, impossible from the internal instruction to move to each target point by turning the head and eye at the same time. Several studies have attempted to demonstrate links between the programming of concurrent head and eye movements for the review, see Jeannerod (1988). These studies predominately have been restricted to single movements rather than movement sequences. Evidence for the concurrent programming of movements of the head and body comes mainly from observations that (i) a sacadic eye movement can occur at about the same time as the onset of electromyographic (EMG) activity in the neck muscles (e.g., Bizzi et al., 1971), and (ii) neck EMG activity can be observed when saccades are programmed while the head is held in place (Bertellotti and Grantyn, 1984).

The research described in the preceding paragraphs has provided several interesting demonstrations of the concurrent programming of eye movements and of the programming of movements responses. These demonstrations, however, have been restricted to a few, relatively simple and artificial laboratory tasks, not necessarily representative of the way the head and eye are used together in more natural situations. We know little about the inherent constraints that make programs for coordinated head and eye movement patterns in the natural behavioral repertoire. Moreover, we know little about factors that make some programs more valuable for the accomplishment of visual information than others. Finally, and most importantly, we know little about the basis for the coordination of head and eye movement patterns in the natural environment.}

In order to begin to understand the kinds of head and eye movement patterns human beings choose during natural tasks, we measured movements of the head and eyes during reading.
We chose to study reading because the eye movement pattern is fairly stereotypical and has been subjected to extensive empirical and theoretical investigation (for review, see O'Regan, 1990). Therefore, we were able to begin with a clear idea of what sort of saccadic patterns to expect. Nevertheless, most of the research on reading (and certainly any research using highly sensitive eye movement) has been done with subjects whose heads were stabilized by bite boards or chin rests, or subjects who were constrained from moving the head through the use of oculargographic recorders. As a result, little or nothing is known about the pattern of eye and head movements that characterize reading when the head is free to move.

To emphasize the naturalistic character of the task, we had subjects read actual pages of text rather than electronic displays with both eyes at a typical reading distance. The distance we used was small enough (29.5 cm) so that we had to measure head translations, in addition to eye and head rotations, in order to obtain an accurate measure of the position of the line of sight along the page of text.

Two other tasks were studied. First, we looked at the eye and head movement pattern when the subject was asked to scan individual letters separated by distances about equal to the length of words in the text we tested. This letter-scanning condition was tested to find out whether characteristics of the head and eye movement pattern were unique to reading, or would be shared with a task making about the same demands on the spatial properties of saccades but making different demands on the cognitive apparatus of the subject. Second, inspired to a large degree by the characteristics of eye and head movements we observed during reading, we asked a subject to execute a variety of unusual head and eye movement patterns. In this experiment, we tried to deliberately decoy the expected spatial relationships between concurrent movements of the head and the eyes. This last experiment introduces a new and potentially promising paradigm that can be used to explore the limits of the capacity of the human being to link concurrent head and eye movements.

Methods

Eye and head movement recording

Two-dimensional rotations of the right and left eyes and of the head relative to earth-fixed coordinates were recorded by the rotating magnetic field monitor at the University of Maryland. Horizontal and vertical angles were measured with an accuracy of 1 minute of arc and were sampled and scored at 488 Hz. These angles were insinuated to translational movements of the head over the range of motions employed in the experiments. [For a more detailed description of this instrument, see Collewijn et al. (1981, 1984a) and Chapter 64, this volume.]

The position of the head in space was measured with an acoustic ranging system that is highly in-house modified SAC Associates 3-D Grafenplot. A spark drive (henceforth, "spark"), placed at the top of the head, emitted 60-kHz ultrasonic pulses whose acoustic wavefronts were picked up by three microphones at a sampling frequency of 61/1. The instrument determined the distance of the spark from each of the microphones based on the propagation times of the sound pulses. These distances were converted to a three-dimensional Cartesian coordinate system. The overall accuracy of the measurement, including all the various sources of imprecision, was about 1 mm.

Subjects

Two of the authors (E. K. and H. C.) served as subjects for the reading experiment. Both are highly experienced eye movement subjects. E. K. is myopic and read with her usual contact lenses. H. C. read without spectacle correction. Another author (R. S.) served as a subject for the second experiment in which head and eye movements were measured during the inspection of a square array of targets. R. S. does not require spectacle correction for distance vision.

Stimuli

Figure 65-1 illustrates the subject and the stimulus used in the reading trials. The stimulus consisted of pages of text from the novel Maxwell's Train (Hyde, 1984). The page of text to be tested for the trial was attached to a wooden board that was mounted on a table top at an angle of 35° with the horizontal. The horizontal distance between the midpoint of the center of rotation of the two eyes and the text was 29.5 cm. At this distance a line of text, which measured 10.7 cm across and contained average 61 characters, subtended 20°.

Stimuli for the letter-scanning condition were pages of text from the same book in which only single letters spaced at intervals approximately equal to the length of words, were visible. In a second experiment, the subject tried to execute a variety of usual and unusual patterns of head and eye movements. Details of this experiment are described later, along with the results.

Procedure for reading and letter-scanning tasks

Each subject was tested in one recording session consisting of 26 trials lasting 30 seconds each. The head was on the bite board (head-fixed condition) for the first and last four trials, and off the bite board (head-free condition) for the middle eight trials of the session. The last trial in each group of bite board trials and the...
last two trials in the group of head-free trials were letter-scanning trials. The rest were reading trials.

Subjects were instructed to read at the same rate as they considered to be their normal pace for the material presented. They were told to start reading at the portion of the text corresponding roughly to eye level when the experimenter gave the signal to begin. A few seconds later the experimenter pushed a button that initiated the collection of data. Subjects read with the expectation that their comprehension of the material would be tested at the end of the recording session.

Calibration session

The experiments were preceded by a brief calibration session in which we measured:

1. The output of the head and eye sensor coils when the head was on the bite board and each eye was fixating directly ahead.
2. The output of the sparkler when positioned (1) at the origin of the three-dimensional coordinate system, and (2) on top of the subject's head while the subject was aligned on the bite board. In this standard bite board position, the midpoint of the center of rotation of the two eyes coincided with the origin of the three-dimensional coordinate system. These two measurements made it possible to determine the location of the center of rotation of each eye during the experimental trials when the sparkler was worn on top of the head.
3. The output of the sparkler and the head and eye sensor coils when the subject fixated, in turn, the letters at the upper left, upper right, lower left, and lower right corners of the page of text.

Data analysis

In the first stage of data analysis the output of the sparkler and the measured head rotation were used to determine the position of the center of rotation of each eye in three-dimensional space (see Chapter 64, this volume; for details). Next, this measurement of the center of rotation of each eye was combined with the measured eye rotation to determine the position of each line of sight on the page of text. Finally, the movements of each line of sight along the page were analyzed to detect saccades, and measure the sizes of these saccades and of the intersaccadic intervals. Saccades were detected by an acceleration criterion whose accuracy was confirmed by inspection of analog records. We ignored saccades, and intersaccadic intervals containing saccades, smaller than 2 mm on the page, which was about the distance between the centers of adjacent characters. Such small saccades are exceedingly rare during normal reading (Cunlitz and Steinman, 1969).

Results

Coordination of head and eye during reading

Head rotations during reading were larger when the head was free than when the head was on the bite board. The average trial standard deviation (S.D.) of head rotations with the head on the bite board was 5.4 minutes of arc for H.C. and 4.1 minutes of arc for E.K. Average S.D.'s with the head free were 42.3 minutes of arc for H.C. and 24.7 minutes of arc for E.K. The S.D.'s with the head free are about twice what is observed when subjects try to hold the head as still as possible without artificial support during maintained fixation (Shenken et al., 1979; Breneman et al., 1982).

Figure 65-2 (top) shows an example of the head and eye movements by H.C. during reading. The top trace shows head rotations and the bottom trace shows rotations of the left eye (rotations of the right eye did not differ appreciably). The pattern of head rotations varied during the trial. During the third and fourth seconds, H.C. made a fairly large lateral 21° rightward head rotation as his eyes moved rightward across the line of text. The saccade returning the eyes to the next line of text was, of course, rapid, but the return sweep of the head took more than 1 second to complete. This means that for nearly 0.5 seconds, H.C. was making saccades to the right, as he began to read a new line, while his head continued to move to the left. Figure 65-2 (top) also shows some fairly fast intersaccadic drifts opposite to the direction of head rotation.

The middle graph in Figure 65-2 shows the total movement of the head (top trace), along with the rotational (middle trace) and translational (bottom trace) components. In all three traces head position is expressed in centimeters along the page of text. These traces represent the position of an imaginary line projected from the center of rotation of the left eye onto the page. The rotational
The reduction in interœccadic drift is again seen in the bottom graph, showing the position of the line of sight on the page, and the moving movements of the eye in space. Unlike H. C., however, the direction of her head movements was nearly opposite to the direction of her saccades.

In summary, the head moves during reading, but not in a haphazard pattern. We found clear differences in the amplitude of the head movements over the course of the trial. Also, in some instances the head moved in the same direction as the reading saccades; in other instances it moved in the opposite direction.

Eye rotations compensated well for head movements, producing a fairly stable line of sight during interœccadic intervals.

**Saccades during reading and scanning with the head fixed and free**

Figure 65–4 (top) shows the average duration of the interœccadic intervals and the average size (in millimeters on the page) of the rightward saccades during reading when the head was on the bite board and when it was free to move. The only reliable differences between the head-fixed and head-free performances were for subject H. C., who had slightly shorter interœccadic intervals and slightly longer saccades when his head was free to move.

There were no differences between the saccadic patterns with the head fixed and with the head free when single letters were scanned (Figure 65–4, bottom). Interœccadic intervals were, however, 40 to 100 ms longer during scanning than during reading. Saccades were also a bit shorter during scanning, but the slightly reduced size of the saccades was not sufficient to account for the increase in interœccadic interval (see Wyman and Steinman, 1960; and Steinman et al., 1979).

The interœccadic intervals observed during reading and during the presumably easier scanning task is a puzzling phenomenon, observed first by Hurvich (1960) in one of the earliest studies of eye movements during reading. The puzzle is why the processing of cognitive material speeds up, rather than slows down, the concurrent motor pattern.

**Interœccadic speeds**

The analysis of interœccadic speeds confirmed that eye rotations compensated well for head movements. Average interœccadic speeds, shown in Figure 65–5, were slightly faster with the head free than with the head on the bite board during the scanning task, but were either the same or slightly faster with the head on the bite board during reading. The interœccadic speeds were small relative to the size of the characters. The largest drift (H. C.’s left eye when he was on the bite board during reading) carried the line of sight only 0.9 mm (about the width of the character) during his brief (160-msec) interœccadic interval. This drift, however, was about 17 sec. This is about five to ten times as fast as the drift speed observed during maintained fixation with the head on a bite board (Steinman et al., 1979) but quite similar to the drift speed observed during maintained fixation when head movements are permitted (Skavenski et al., 1979; Steinman and Collewijn, 1980; Steinman et al., 1982).

**Limits of spatial and temporal coordination of the eye and head**

Our results thus far show a clear, but flexible, relationship between eye movements of the eye and head. This would seem to suggest that human beings have the capacity to program different sorts of spatial and temporal patterns of head and eye movements depending on strategy and choice. We sought to understand the limits of this flexibility by asking a subject (R. S.) to attempt a
Fig. 65-4. (READ) Mean intersaccadic interval (top) and mean size of rightward saccades on the page of text (bottom) during reading. (SCAN) Mean intersaccadic interval (top) and mean size of rightward saccades on the page of text during scanning individual letters. Vertical bars indicate ± S.E. Means are based on 600 to 700 saccades for reading and on 150 to 200 saccades for scanning.
variety of natural, and some unusual, head and eye movement patterns.

He looked at an array of eight small, brightly colored square targets, arranged in a square pattern on a distant wall (7.9 m). Adjacent targets were separated by 5.5°. The room lights were left on so that the subject saw the stimuli in the typical cluttered laboratory environment. We measured rotations of the head and the right eye. The use of distant targets made it possible to disperse the reading of head translations (Steinman et al., 1982).

Figure 65—6 (top) shows head and eye movements when R. S. was scanning the perimeter of the rectangle, looking from one target to the next, while trying to keep his head as still as possible. Head movements were quite modest, comparable to those measured while attempting to keep the head as still as possible during maintained fixation (Kasakowski et al., 1979; Steinman et al., 1982). The graph in the middle of Figure 65—6 shows head and eye movements when R. S. was asked to adopt what he considered to be his natural scanning pattern, and not to worry about producing any particular pattern of head or eye movements. Under this instruction head movements became larger and the saccade rate increased as well. The bottom graph shows head and eye movements when the subject was asked to scan as fast as possible. Both the saccade rate and the amplitude of the head movements increased. Apparently, freedom to move the head in concert with the eye increases the speed of scanning.

We next asked the subject to look in the center of the array of targets and try to move the eyes in one direction and the head in the opposite direction. He managed only one instance (see the top graph of Figure 65—7, the 13th second of the trial) in which the head moved to the left and the eyes moved to the right. He had more success at first when he deliberately slowed the head movements (bottom graph), but even here he found he usually fell back into synchrony. The subject could move his head up while moving the eyes to the right (Fig. 65—7, middle) but he made frequent, inappropriate horizontal head movements (one was opposite to the direction of the saccade) along with the required horizontal saccades.

In Figure 65—8 the subject scanned the array of targets while shaking his head either horizontally (topgraph) or vertically (bottom graph). Scanning was more erratic than in the earlier performance (Fig. 65—6), but far more interesting were the large spontaneous head movements, almost equal to the angular separation of the targets on the orthogonal meridian. The saccadic temporal pattern of these emergent head movements corresponded to the saccadic temporal pattern of the saccades on the same meridian.

These scanning tasks show a natural tendency for a spatial and temporal link between the movements of head and eyes. The link is not compulsory—may be broken with effort—but in the absence of the concerted effort to execute independent patterns of head and eye movement, the natural tendency is to produce a common spatial and temporal pattern. It is extremely difficult and quite unnatural to move against this tendency.

Discussion

Our investigations of head and eye movements during reading and during scanning, and our attempts to underscore the performance of unusual head-eye movement combinations, have revealed three characteristics about the normal coordination of head and eye movements.

First, moving the head can increase the rate of saccades. This was most apparent in two circumstances: the reading trials of H. C. and the scanning of the array of targets by R. S. Allowing the head to move has also been found to shorten saccadic latency during certain target-tracking tasks (see Chapter 71, this volume). We found that moving the head did not always increase saccade rates, however. For example, saccade rates were the same for head-fixed and head-free reading for E. K. and for scanning of the individual letters for both H. C. and E. K. We suspect that the discrepancy is due to the relative difficulty of the different tasks, with head movements being more helpful when tasks were more demanding. Scanning the array of targets may have benefited from head movements because the saccades were large (about 5° to 6°) relative to the saccades during reading (about 3°). The saccades made by H. C. during reading may have benefited from head movements because the inter-saccadic intervals during reading were shorter than those of E. K. and shorter than either of their inter-saccadic intervals during letter scanning.
This pattern of results suggests that head movements, rather than having a uniform and compulsory effect on saccade rates, are instead most valuable when saccadic performance is pushed toward its limits. The problem now is to understand why head movements should be able to expand saccadic capacity. Does freezing the head to move help the eyes, or does holding the head interfere with oculomotor performance? We prefer the second alternative. If telling oneself to look at a target leads naturally to intransitive instructions to move both the head and the eyes (Zingale and Kawler, 1987), then perhaps the effort to keep the head still, either on or off the bite board, impairs the ability to move the eyes.

The second characteristic we observed is that the ability to execute unusual patterns of head and eye movements is different during a task with clear cognitive components (reading) than during less natural tasks in which the observer is simply trying to direct the eye to an eccentric target devoid of any cognitive significance (something we probably rarely do in natural viewing outside the laboratory). For example, we found instances in

which the head and eyes moved in opposite directions during reading, a pattern that could be created only with great effort during scanning of targets. We also replicated the classical observation that inter-saccadic intervals are substantially shorter during reading than during scanning (Ruer, 1960). These observations point to the importance of high-level control in the programming of movement. By high-level control, we are referring to unspecifie cognititve involvement but more specifically, to the way in which the initial representation of the commands to orient the head and eyes are intertwined to the ongoing cognitive processes involved in the spatial analysis of the visual scene. This link has been proposed for the programming of smooth and saccadic eye movements, but its extent and nature are certainly not well understood at present (see Kawler, 1990, for review).

Fig. 65-6. Horizontal (H) and vertical (V) rotations of the head and right eye in space for subject R. S. as he scanned the square array of targets while trying to keep his head as still as possible (top), scanned the array in a natural manner (middle), and scanned the array as fast as possible (bottom).

Fig. 65-7. Horizontal (H) and vertical (V) rotations of the head and right eye in space for subject R. S. as he tried to move his head and eyes in opposite horizontal directions (top), in orthogonal directions (middle), and in opposite horizontal directions with slow head movements (bottom).
Finally, our results revealed a natural tendency to program head and eye movements concurrently in spatial and temporal patterns. We saw this in the general agreement of the pattern of head and head motions during reading, and more vividly in the tendency of R. K. to move his head in the direction and at the same time as he made saccades during scanning, unless he made explicit efforts to avoid doing this. Distraction by another task (e.g., shaking the head along the horizontal or vertical meridian) was sufficient to evoke large head movements entrained with the pattern of saccades. These observations are consistent with the suggestion made earlier in the discussion that there is a natural tendency to formulate a single, high-level motor program to orient both head and eyes, rather than to issue head and eye movement commands separately. We found that separate commands to the head and eyes are possible, but only with special effort and, perhaps, with some sacrifice in the precision of the visual or oculomotor performance.

**Future Directions**

The nature of the central program to orient head and eyes to selected visual targets is, as of now, poorly understood, although several of the basic phenomena and problems have been identified. Perhaps progress can be made by continuing the approach described here—the exploration of scanning during natural tasks and the use of special tasks to tax the capacity of the system by requiring unusual patterns of head and eye movements. The latter approach seems particularly promising: failures of perceptual discrimination have told us much about the operation of sensory systems. Perhaps the failure to be able to execute "unnatural" patterns of coordinated head and eye movements will provide a technique for understanding the nature and organization of the underlying motor programs.

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