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Section 3

Eye and head coordination in reading: roles of head movement and cognitive control

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Abstract

Simultaneous recording of eye and head movements during reading revealed that head movements consisted of two components: a modulatory-velocity component coupled to eye saccades, and a constant-velocity component that was independent of eye saccades. Whereas the constant-velocity component increased as subjects repeatedly read the same text, neither the magnitude of the modulatory-velocity component, nor the amplitude of the eye movement, increased. This outcome could be closely simulated when the head movement command was assumed to be stronger, and issued earlier with repeated reading. These results suggest that higher-level processes related to text familiarity modulate eye–head coordination through head movements.

Keywords: Human; Cognition; Reading; Saccadic eye movement; Gaze control

1. Introduction

Normal eye movements of skilled readers consist of a series of fixations and saccadic eye movements (see for a review O'Regan, 1990). Thus, eye position plotted against time forms a peculiar staircase pattern, a motor strategy that emerges as the reader becomes more skillful. Most studies on eye movement control in reading have focused on factors affecting spatial and temporal parameters of the movement, such as saccade size, fixation duration, and location in words. While several factors were successfully isolated in controlling these parameters, the precise mechanism by which these parameters are influenced remains controversial (see for reviews O'Regan, Vitu, Radach & Kerr, 1994; Rayner, 1994; Rayner, Sara & Raney, 1996).

The direction of gaze is determined by orienting the eyes in the head, and the head in space. However, with few exceptions (e.g. Kowler, Pizlo, Zhu, Erkelens, Steinman & Collewijn, 1992, who examined eye–head coordination during various cognitive tasks), the procedures adopted in most studies measuring eye movements in reading required immobilizing the head, and so the pattern of head movements and their roles in reading have been largely undetermined. Vilis (1994) offered one possible role of head movements in reading, theorizing that these reduce the torsional disparity elicited when a head-fixed reader directs his/her gaze to an extreme tertiary eye position. Several issues are of interest besides this mechanical aspect of head movements. First, since fixation stability diminishes when the head moves (Skavenski, Hansen, Steinman & Winterson, 1979; Ferman, Collewijn, Jansen & Van den Berg, 1987), and since the contribution of head movements is minimal for small gaze shifts ($<20°$) (Tomlinson & Bahra, 1986a,b; Guitton & Volle, 1987; Phillips, Ling, Fuchs, Siebold & Plorde, 1995; Freedman & Sparks, 1997), an obvious question is whether head movements are intentionally suppressed even when the head is free to move. If the head movement is not suppressed, is it coupled to the eye movement, or independently controlled? Second, head movements are strongly influenced by cognitive factors, and therefore in head-free

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reading they may predominantly reflect the cognitive influences that have been shown for eye movements in head-fixed reading, and thereby decouple eye–head coordination. Thus, a theoretical issue is whether a global control based on semantic processing is preferentially directed to head movements, a control strategy that would be confounded in head-fixed conditions. Since the direction and expected excursion of impending gaze shifts are known, the head may be programmed to move continuously with a predetermined velocity influenced by cognitive factors, such as text familiarity. In this study, I tried to determine the pattern of gaze control and roles of head movements in head-free reading.

2. Methods

Three college students, all native Korean speakers, volunteered to participate as subjects. For each, the nature and possible consequences of the experiments were explained, and informed consent to participate was obtained. The subjects had no prior history of ocular motility disorders, and were not taking any medications.

The scleral searched positions coil method (Robinson, 1963) was used for monitoring gaze and head. For each subject, after the conjunctiva was anesthetized with 0.5% proparacaine hydrochloride (Alcon, Belgium), a search coil (Skalar Medical, Netherlands) was placed around the cornea, and another search coil (38 mm in diameter, made of ten turns of copper wire insulated with enamel) was mounted onto a tightly-fitting hat. The subject was seated so that the head coil was placed at the center of alternating magnetic fields driven at frequencies of 50 and 75 kHz in spatial quadrature (Remmel, 1984). A rigid wooden frame supported the subjects arms and shoulders allowing virtually no torso movements, and thereby reducing translational head movements.

The reading material was a portion of a contemporary Korean short story, *HyangSoo* (by Hyoseok Lee), printed in 14 horizontal lines, each 58 cm long, mounted inside a cylindrical panel. The text was easy reading for college students. The viewing distance was approximately 35 cm. Measured from the eyes, the subtended angle of the text width was 90°, with one Korean character subtending about 38 min of arc[1]. Subjects were instructed to read the text naturally while maintaining the body as still as possible, and were informed that a comprehension test would be delivered after the experiment. To reveal the changes reflecting non-visual, cognitive processes related to the text familiarity, each subject was directed to read the same text three times (Hyona & Niemi, 1990). The signals related to the horizontal and vertical directions of gaze and head positions were sampled at a rate of 250 Hz with 12-bit resolution, displayed on an X–Y oscilloscope and a graphics monitor, and stored for off-line analysis. The head coil was calibrated beforehand using a model head, and the eye coil was calibrated during the experiment by having the subjects fixate LEDs located at known positions. The eye position (in head reference) was obtained by subtracting the position of the head (in space reference) from that of the gaze direction[2].

The analysis was restricted to periods with forward saccades. During off-line analysis, gaze and head-position signals were filtered with a box-car window of 16 ms, and displayed on a computer monitor. The position, velocity, and sometimes instantaneous acceleration traces of the gaze, eye and head plotted against time were displayed on a graphics monitor. By visually inspecting these traces, 124 time periods containing only forward gaze saccades and a monotonic change of head position were isolated for subsequent analysis. These periods ranged from 1000 to 3500 ms, averaging 2061 ms with a standard deviation of 547 ms. Only one period was sampled every 9.5 s, which was the duration of one block of data storage. To examine the temporal coupling of eye and head movements, a cross correlation function between instantaneous eye and head velocity was calculated for each time period, and the time of occurrence of the peak of this function was taken as an index for an overt temporal relation between the two movements.

3. Results

Figure 1 illustrates a representative record from a period of head-free reading. During forward (rightward) gaze saccades, horizontal head position (H)

[1] Hangul, the written form of Korean, is based on 24 phonetic letters. Letters representing vowels and consonants are grouped into visually distinct characters that represent syllables, which are usually read from left to right, or occasionally from up to down.

[2] There are two sources of potential error in these signals. Since the rotation centers of the eye and head do not coincide, gaze amplitude is not equivalent to the sum of the rotation of the eye in the head and the head rotation (Blakemore & Donaghy, 1980; Collewijn, Conjin, & Tamminga, 1982). Thus, an error occurs when head position is subtracted from gaze position to obtain the eye position in the head. However, since analyses in this study are mainly concerned with velocities of head and gaze movements, errors due to the eccentric rotations are not cumulative, and thus are negligible. I accordingly chose not to correct this error. Another source of error in the signal is due to head translation. With the 0.57 m square field coil used here, the magnetic field is uniform to less than 1% within the central 0.05 m (Remmel, 1991), which was about the maximal head translation occurring during these experiments, as estimated with direct off-line measurements with a ruler for these same conditions. Thus, these data are potentially subject to a slight but negligible contamination.

changed continuously to the right, while horizontal gaze position (G) showed a series of fixations and saccades. The pattern of gaze shift was reminiscent of the staircase pattern characterizing eye movements in head-fixed conditions (see O'Regan, 1990, for a review). During the fixation phase of gaze, the derived horizontal eye position (E in Fig. 1B), thus moved slowly to the left, compensating for the continuous head movement in the opposite direction. Fixation periods were defined as epochs for which gaze velocity was less than 20 deg/s. The mean standard deviation of gaze position during fixation periods for all three reading sessions was 0.06° for the subject shown in Fig. 1, and 0.03° for the other two subjects, indicating that head movements were closely compensated for by eye movements, and that gaze was maintained stable during fixation.

While horizontal head position changed monotonically, a fine-scale oscillatory modulation was apparent in the instantaneous head velocity (Fig. 1C). These modulations of head velocity were often coupled to gaze saccades (Fig. 1C; Fig. 2), suggesting that a common command drives both the eye and head motor systems, at least for some periods. For the coupled gaze saccades, head velocity started to increase earlier than the onset of the gaze saccade (Fig. 2), as when shifting gaze to predictable targets (Bizzi, Kalil & Morasso, 1972). During this initial phase of movement, the eyes moved to the left (negative velocity in Fig. 2A and C) to compensate for the rightward head movement, and to maintain fixation until the onset of the gaze saccade, which was then carried out by eye and head movements in the same direction. Head velocity was typically maximal around the offset of the gaze saccade, and then decreased. The distribution of the time of occurrence of the peak cross-correlation between eye and head velocities (the lag) showed a central tendency, indicating that head movements were coupled to eye movements (Fig. 3). The pattern of distribution of the lag was slightly

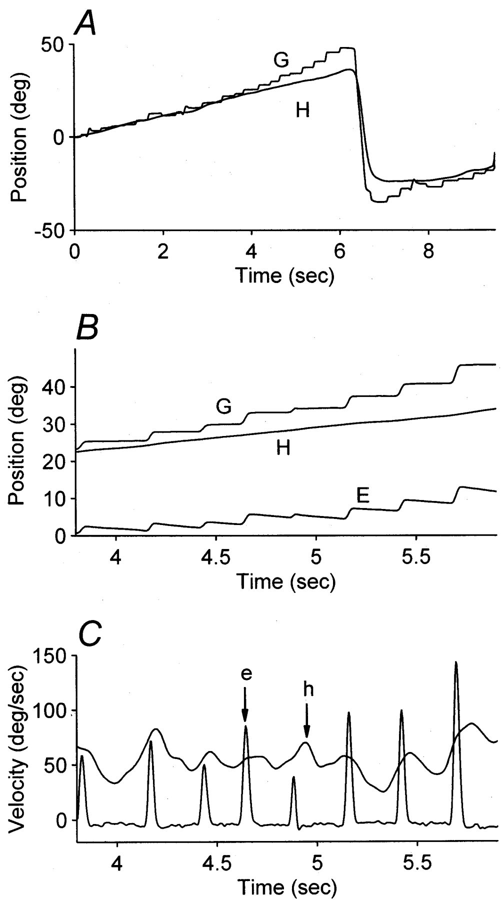

Fig. 1. Gaze and head movements during head-free reading. (A) Horizontal positions of the gaze (G) and the head (H) from a typical experiment. Upward deflections correspond to rightward movements. Large downward (leftward) deflections represent a gaze shift to the next line of text. (B) One sampled period (from 3.8 to 6 s in A) is shown with eye position (E, derived by subtracting H from G). (C) Instantaneous velocities of the eye and head movements shown in B. Head velocity (h) is multiplied by ten times to reveal its oscillation in relation to eye velocity (e). This example is drawn from 124 selected time periods containing only forward gaze saccades.

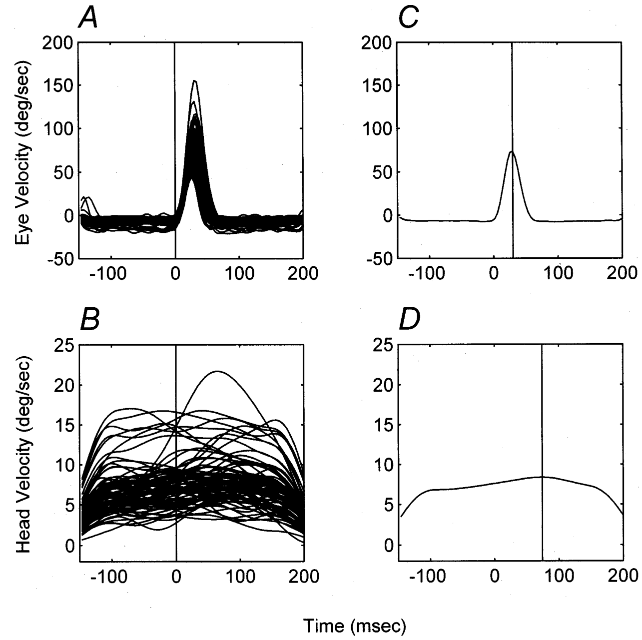

Fig. 2. Coupling between eye and head movements. (A) All 84 saccades from the periods containing only forward saccades obtained in one session (subject IA, session 3) were isolated, and their velocity traces aligned with the onset of eye movement (vertical line), as determined by a velocity criterion. Before and after saccades, the eyes were often moving to the left in the orbit to compensate for the rightward head movement, showing negative velocities in some traces. (B) The velocities of 84 head movements during matching periods, also aligned at the onset of eye movement (vertical line). (C) Mean velocity trace of those plotted in A, with a vertical line at its peak. (D) Mean head velocity for the data in C, with a vertical line at its peak. Note that head velocity starts increasing before the eye saccade, and the peak of head velocity lags behind that of the eye—by 44 ms in this example. Exclusion of one outlying trace in B did not affect this lag.

different among subjects (not shown), but it did not differ across sessions for a given subject. It should be pointed out that modulation of head velocity was not always coupled to a gaze saccade, and not all individual gaze saccades were accompanied by such modulations.

The oscillatory modulations of head velocity were superimposed on a constant velocity, (Fig. 1C; Fig. 4A), which was obtained by subtracting half the mean magnitude of velocity modulation from the mean head velocity (see Fig. 4 legend for detail). One can thus distinguish two components of head velocity during reading: a modulatory-velocity component coupled to gaze saccades, and a constant-velocity component. These two components appeared to have different roles, since repeated reading differentially affected the two. The constant-velocity component differed among subjects and across repeated reading sessions (Fig. 4B; Table 1), indicating that it reflected higher-level processes related to text familiarity.

Unlike the constant-velocity component of head velocity, the modulatory-velocity component did not differ among subjects or across sessions. Two related measures of the modulatory-velocity component were analyzed. The magnitude of velocity modulation (Fig. 4A) did not differ across session ($P = 0.86$) or across subject ($P = 0.75$), and there was no significant interaction between the two. Also, the amplitude of head movement contributed by the head 'velocity pulse' (see legend to Fig. 4A) did not differ across subjects ($P = 0.22$) or session ($P = 0.85$), and there was no significant interaction. The Pearson product-moment correlation coefficient between these two measures was 0.81 ($P < 0.0001$), indicating that the two are highly correlated with each other, although they are not the same measure. The differential effects of repetition on the two components did not depend on the width of the win-

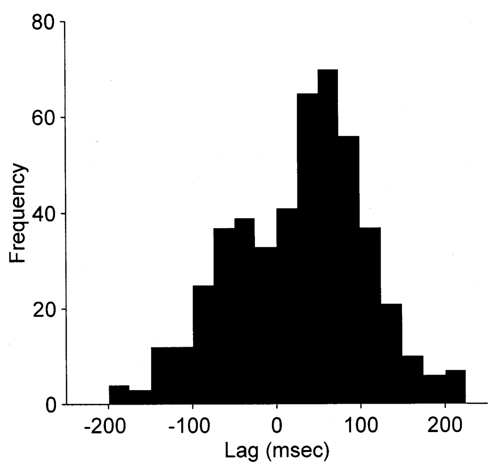

Fig. 3. Histogram of lag (time shift) associated with maximum of cross-correlation function between the eye and head velocities during forward reading. Data are pooled over all subjects and all sessions. Median of the distribution is 24 ms.

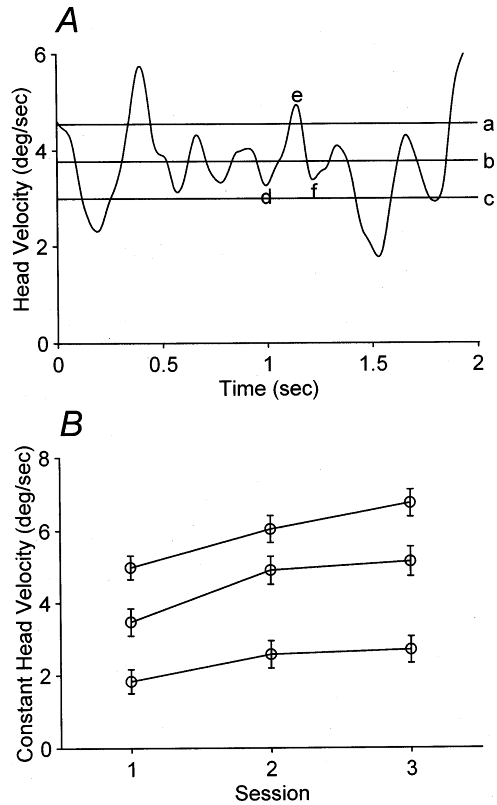

Fig. 4. Two components of head velocity and effects of repeated reading. (A) Determination of the constant and oscillatory components of the head velocity. Instantaneous head velocity is redrawn from the example in Fig. 1C. First, the mean level of head velocity (b) during this period was obtained. Next, the magnitude of velocity modulation was determined after smoothing instantaneous velocity with a hanning window spanning 120 ms. The trace was divided into segments of velocity modulation by the points in time when head acceleration crossed zero (d–e or e–f, for example). The sum of absolute velocity changes of these segments divided by the number of segments was taken as the mean magnitude (distance a to c) of velocity modulation for each period. The constant level of head velocity (c) was obtained by subtracting half the mean magnitude of velocity modulation from the mean head velocity (b). Thus, the instantaneous velocity may drop below the constant velocity. Alternatively, one can assume that head velocity oscillates around a mean velocity. Both assumptions are based upon a two component process, but the constant-velocity level would differ between the two. A pair of rising (d–e) and falling (e–f) segments of velocity modulation is referred to as a 'velocity pulse' in the sense that 'velocity pulses' are added to the constant background velocity. The amplitude of head movement contributed by the 'velocity pulse' was obtained in the following way. Based on zero-crossing times of head acceleration, the duration of the 'velocity pulse' (d–f for an example) was determined, and the instantaneous head velocity minus the constant-velocity component was integrated over this duration to yield the amplitude of head movement for that 'velocity pulse'. The mean amplitude of head movement made by 'velocity pulse' in 122 sample periods (excluding two periods for which the computer algorithm failed because of inadequate number of pulses) was 0.45° (± 0.36), ranging from 0.03 to 2.21°. (B) The constant-velocity component of head movements across sessions for three subjects. The bars represent standard errors of the mean.

dow chosen to filter instantaneous velocity. With widths of either 40 or 16 ms, the effects of repetition on the constant-velocity component were significant, ($P <$ 0.0005 in both cases), whereas the effects on both the magnitude of modulatory-velocity component of head movements and the amplitude of head movement contributed by the velocity pulse were not statistically significant.

The gaze (combined eye and head, i.e. the eye-coil signal before subtracting the head-coil signal) saccade amplitude increased as subjects read the same text repeatedly ($F_{(2,883)} = 4.70$, $P < 0.01$), just as eye saccade amplitude increases in head-fixed reading (Hyona & Niemi, 1990). In head-free reading, however, the change in gaze saccade amplitude was mainly contributed by head movements. As the constant-velocity component of head movements increased with repeated reading, the amplitude of head movements during gaze saccades increased ($F_{(2,883)} = 17.24$, $P < 0.001$), whereas the amplitude of the eye movements changed insignificantly ($F_{(2,883)} = 3.18$, $P > 0.04$). Across all three subjects, mean gaze amplitude was 2.57°, spanning approximately four characters. Head movements contributed approximately 16% of individual gaze movements.

Although these results are consistent with the idea that increased familiarity with text is reflected in the constant-velocity component of head movements, but not in the gaze saccades that consisted of eye saccades and eye-coupled, modulatory-velocity components of the head movements, one must consider the possibility that the constant-velocity component is actually an epiphenomenon. This could happen if the head moves only as a part of gaze saccades, and if gaze saccades occur so often that sequential head movements overlap due to their slow time course, producing an artefactual constant-velocity component. In order to see if the data are consistent with this possibility, a computer simulation was used (Fig. 5). It was assumed that single pulses of Gaussian motor commands give rise to head movements, and that the head-velocity faithfully reflects the pattern of the command pulse. It is known that for slow voluntary head movements, the mechanical system follows neural signals with a pure time delay (Stark, 1968). The average period of head velocity modulation

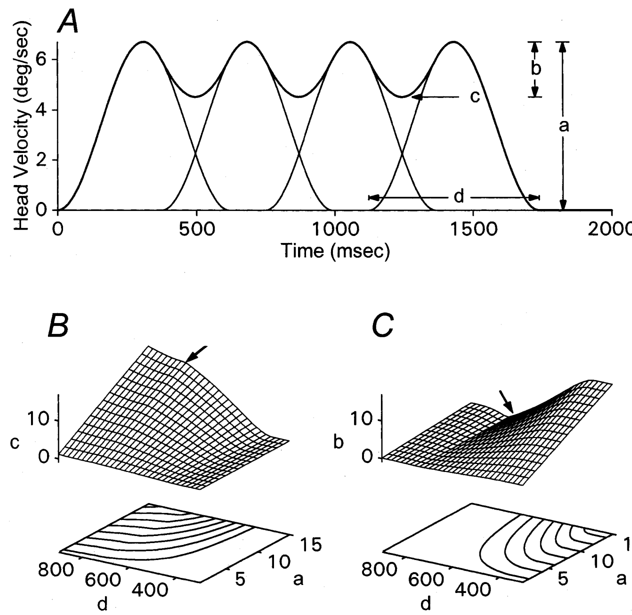

Fig. 5. A computer simulation of head velocity. (A) Hypothetical process determining head velocity. Four Gaussian pulses of motor command giving rise to head movements are 374 ms apart, which was the average period of head velocity modulation in this study. When the base width of the Gaussian is large enough and the pulses are summed, a constant-velocity component, as indicated by 'c', results. A goal of the simulation was to find the Gaussian height ('a') and the base width ('d') that closely matched experimentally-obtained values of modulation magnitude ('b') and the constant-velocity level ('c'), as shown in Table 2. (B,C) Results of simulation. Constant velocity (c, deg/s) and modulation amplitude (b, deg) as functions of pulse width (d, ms) and pulse height (a, deg) are shown in 3-D surface plots along with contour plots. Note that increase in Gaussian height (a) increases both constant (Fig. 5B) and modulatory (Fig. 5C) velocity of head movements, and that increase in Gaussian base width (d) increases constant-velocity (Fig. 5B), but decreases modulatory-velocity (Fig. 5C). Beyond width of approximately 740 ms (arrows), very little modulation of velocity is predicted (flat part in Fig. 5C).

in this study, as determined from the interval between adjacent peaks of the instantaneous head velocity, was 374 ms, and this did not differ across repeated sessions ($F_{(2,116)} = 1.52$, $P = 0.970$), so Gaussian command pulses with varying amplitude and width were generated every 374 ms[3]. An example of one simulation is shown in Fig. 5A. The results of such simulations revealed that increases in pulse amplitude (Gaussian height) augmented both the constant- and modulatory-velocity of head movements (Fig. 5B,C). Increasing the width of the command pulse (Gaussian base), however, increased the constant-velocity component, but de-

Table 1
ANOVA of constant head velocity

Source	SS	df	MS	F
Subject	126.71	2	63.35	87.45[a]
Session	18.15	2	9.08	12.53[a]
Sub × Sess	3.09	4	0.76	1.05
Within	83.31	115	0.72	
Total	231.26	123		

[a] $P < 0.001$.

[3] The mean interval between onsets of adjacent gaze saccades (determined with a velocity criterion of 20 deg/s) was 290 ms. Gaze saccades were more frequent than the modulations of head movements, because not all eye saccades were coupled to these modulations. The frequency of gaze also changed insignificantly with repetition as judged with 2-way (subject × session) analyses of variance of the interval between onset times of gaze saccades ($P > 0.1$).

creased the magnitude of velocity oscillation (Fig. 5B,C). In order to reproduce the effects of repeated reading (i.e. augmented constant-velocity, but unchanging oscillatory magnitude), it was necessary to increase both the width and amplitude of the command pulse. Table 2 shows the widths and heights of the command pulse that replicated the experimental values.

4. Discussion

Previous studies have reported that small amplitude gaze shifts are accomplished by eye movements alone (Guitton & Volle, 1987; Freedman & Sparks, 1997). The coupling of head movements to small eye saccades that was observed in this study was rather unexpected, since the gaze saccades were less than 3° on average. Whereas in most studies examining eye and head coordination, the line of sight shifts from the primary position to targets presented at unexpected times and locations, and then resets to the primary position before another centrifugal shift of gaze, in reading each gaze saccade not only shifts the line of sight, but also alters the starting position of the eye in the orbit for subsequent gaze saccades. Coupling of the head movements, thus, keeps the eyes relatively central in the orbits, and this may invoke head movements, even though individual gaze saccades are small.

The text used in this study subtends 90° of visual angle, which is unusually large for most text-reading situations. Andre-Deshays, Berthoz and Revel (1988) showed that the activity of neck muscles tonically increased when the gaze shifted to the ipsilateral side, and as can be seen in Fig. 1B, the eye becomes increasingly eccentric in the orbits as the gaze reaches toward the text margin. This suggested a possibility of differential coupling during a reading wide text. However, coupling between the eye and head also occurred with narrower text (subtending approximately 50°), and also consistently occurred in vertical reading, and in following a laser target sequentially stepped by a pair of mirror-galvanometers in either horizontal and vertical directions mimicking spatial and temporal patterns of gaze saccades (Seo & Lee, in preparation). These results suggest that the coupling between the eye and head is a general strategy for continual sampling of information, which is consistent with the idea previously suggested by Kowler et al. (1992) that there is a natural tendency to issue a single motor commands to orient both head and eyes, rather than separate motor commands to the head and eyes. Effects of using a wide text on the pattern of eye–head coordination, however, were not fully explored in this study.

The modulatory-velocity component of the head movement, although small in amplitude, should not be confused with 'wiggling' movements described by Skavenski et al. (1979). The oscillatory modulation described in this report is of much greater amplitude than these 'wiggling' head movements, which were only about 6 min of arc over the frequency range of 0–7 Hz. Furthermore, the distribution of the maxima of the cross correlation between the head and eye velocity had a distinct peak that was fairly consistent across the subjects and across sessions.

Although periods of backward saccades in the middle of the text line and gaze return (to the beginning of the next line) were not the focus of this report, a few observations related to backward saccades are warranted to note. The pattern of gaze return differed across subjects, both for the amplitude of the head return ($F_{(2,95)} = 159.50$, $P < 0.0001$) (and consequently the proportion of the head component to the total gaze shift), and for the amplitude of the primary gaze return ($F_{(2,95)} = 23.60$, $P < 0.0001$). The duration of the movements, however, did not show any significant individual differences. Thus the velocities of both the head and gaze return were significantly different among subjects ($P < 0.0001$ in both cases). The pooled average of the duration of the gaze movement was 253.9($\pm$45.5) ms, while that of the head was 696.3($\pm$110.98), the difference being highly significant. Thus the head often continued moving even after the eye completed the return and started to read the next line.

The nature of events triggering gaze shifts in text reading is difficult to define. However, the temporal relation between the gaze and head movement onsets raises a possibility that gaze shifts during text reading may provide an opportunity for studying voluntarily-initiated gaze shifts in a fairy controlled condition. For targets of unpredictable onset time and location, the

Table 2
Parameters of head movements and command pulse[a]

Session	Constant velocity (deg/s)	Modulatory velocity (deg/s)	Width (ms)	Height (deg/s)
1	3.41 (3.40)	2.29 (2.28)	593	5.7
2	4.49 (4.50)	2.21 (2.20)	617	6.7
3	4.95 (4.86)	2.26 (2.37)	623	7.2

[a] The width and height of the pulse Gaussians were varied to find values that closely simulate the empirically-determined constant and modulatory head velocities. For comparison, experimental values are also shown in parentheses. Note that the width and height of the Gaussian command pulse increases with the reading session.

eye preceded the head by approximately 40 ms, but for predictable targets, the head preceded the eye by 150–200 ms (Bizzi et al., 1972). In reading, the head started to move earlier than the eye by approximately 50–100 ms, as can be seen in Fig. 1, between temporal delays of the triggered and predictive modes.

Using a similar paradigm of repeated reading, but with head-fixed subjects, Hyona and Niemi (1990) reported that enhanced familiarity with the text increases the amplitude of saccadic eye movements, suggesting that cognitive processes influence eye movement control. Results obtained in the current study indicated that the change in the size of gaze shifts associated with text familiarity was preferentially reflected in head movements. Increased familiarity with the text was reflected in the constant-velocity component of the head movement, but not in the gaze saccades that consisted of eye saccades and eye-coupled, modulatory-velocity components of the head movements. I propose that the control related to relatively global parameters is preferentially directed toward the head movement.

Surprisingly, the simple model of the Gaussian command pulse could closely explain much of changes in head velocity parameters with repeated reading. Changes in head velocity parameters, including the increase in constant velocity during the second session, could be replicated by increasing pulse width by 24 ms and pulse height by 18% (Table 2). Therefore, the changes observed after repeated reading appear to occur when the head control system issues command pulses of elevated magnitude for lengthened duration. This suggests that the motor command for head movement is issued earlier after repeated reading relative to the eye movement, because the time of maximal cross correlation between the head and eye velocities did not change across the reading session. The earlier head motor command would not be expected if the head movement is a mere mechanical consequence of the limit of oculomotor range, or if the faster head movement only reflects the requirements of faster gaze movements. Rather, it suggests that a cognitive factor related to text familiarity modulates the mode of eye–head coordination, and that the change in head movements might be controlled by a higher cognitive system.

The pattern of head movement during reading was complex. Modulation of head velocity was not always coupled to a gaze saccade, and not all individual gaze saccades were accompanied by such modulations. Furthermore, occasionally no discernible modulation of head velocity was observed. Results of the computer simulation show that with large pulse widths ($>$ approximately 740 ms), modulation of head movement disappears (Fig. 5C) resulting in an apparent lack of coupling between the eye and head. Thus weaker coupling between the eye and head is predicted with easier and more familiar text. The factors determining the coupling and de-coupling of eye and head coordination, and the generality of these factors for various information-seeking processes are open questions.

Regarding the two components of head velocity, two separate interpretations are possible. First, a constant-velocity and a velocity-modulatory component may be controlled via two parallel pathways. It is possible that at least some of the high-level gaze control related to non-surface, cognitive features is directed to the head via a privileged pathway, and reflected in the constant-velocity component, whereas a low-level, text-sampling process coordinates the eye and head movements in synchrony as manifested in the gaze-coupled velocity pulse. Even when the head is restrained, EMG activity is recorded from the neck muscle in synchrony with gaze shifts (Grantyn & Berthoz, 1987; Andre-Deshays, Revel & Berthoz, 1991), but from our daily experience it is clear that we can intentionally suppress the head movement during gaze shifts, consistent with the privileged pathway model for control of head movements. On the other hand, the computer simulation showed that a simple model based on gaze-coupled head movements alone can reproduce the empirical results, raising the possibility that an earlier and stronger issuing of head movements systematically increases the constant-velocity component of the head, while the modulatory-velocity component of the head remains unchanged. This interpretation is consistent with results of Moschner and Zangemeister (1993), who found that highly predictable target steps resulted in a relatively earlier onset of head movements, and an increase of the heads contribution. Although the results obtained in the current study can not determine whether the constant- and modulatory-velocity components of the head movement are two independent parameters controlled via parallel pathways, or an artifact of overlapped head pulses, in either interpretation, the head movement is the target of high level control, leaving the eye movement relatively independent of cognitive control. It appears that a higher level system modulates eye–head coordination, and that this control is primarily exerted through the head movement.

Reading has commonly been regarded as composed of dual processes: perceptual processes extract visual information, and cognitive processes utilize it (for a review see McConkie, Reddix & Zola, 1992). There has been a controversy as to whether or not the information-gathering aspects are influenced by high level processes (O'Regan, Vitu, Radach & Kerr, 1994; Rayner, 1994). The differential effects of repeated reading on eye and head movements suggest that the information gathering-process itself is heterogeneous, consisting of components both dependent and independent of cognitive control.

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