Coordination of Eye and Head Movements during Reading

Frank Antony Proudlock, Himanshu Shekhar, and Irene Gottlob

Purpose. There is little information regarding the characteristics of head movements during reading. This study was undertaken to investigate horizontal and vertical head movements during two different reading tasks.

Methods. Head and eye movements were monitored with an infrared pupil and head tracker in 15 subjects during repeated reading of text from an A4-sized card and a card 90° wide. In addition, head and eye movements were recorded in 45 subjects to compare head movement propensity during an A4 text-reading task and a saccadic task of an equivalent gaze shift.

Results. During the A4 standard reading task, horizontal and vertical head movements accounted for 4.7% and 28.7% of the gaze shift, respectively. During the 90° text reading, horizontal head movements accounted for 40.3% of the gaze amplitude, and vertical head movements accounted for 28.4%. Horizontal gaze velocities increased significantly on repeated A4 and 90° text readings, as did horizontal head velocities and amplitudes. Reading head movement propensities were significantly smaller than saccadic head movement propensities ($P < 0.001$).

Conclusions. Head movement strategies are rapidly switched between the A4 and 90° text-reading paradigms. They are minimized during A4 text reading but actively assist the gaze strategy during 90° text reading. Horizontal head movement is reduced during A4 reading compared to the equivalent saccadic task and may be suppressed to improve fixation stability. The results support the view that the head and eye movement system is a highly coupled but extremely flexible system. (*Invest Ophthalmol Vis Sci.* 2003;44:2991–2998) DOI: 10.1167/iovs.02-1315

Maintenance of stable gaze, the sum of eye position relative to head and head position relative to space, is essential for reading. Although eye movement strategies used during reading have been investigated extensively,[1,2] the role of head movements in reading is poorly understood. Foveate animals possess the capacity to make saccadic eye movements independent of the head.[3] It has been recently demonstrated that humans also benefit from a highly adaptable gaze control system in which the gaze command can be rapidly transferring onto either eye or head systems (Gottlob I, Proudlock FA, ARVO Abstract 3345, 2001).[4,5] Consequently, it is possible that head movements could be unrelated to the gaze strategy used during reading and are simply compensated for by the vestibulo-ocular reflex. In contrast, head movements may provide some useful function in the reading task, either by assisting the gaze strategy or by being actively suppressed to improve stable fixation.

Only two groups have investigated the patterns of horizontal head movements during reading, with contrasting results. Kowler et al.[6] has observed small inconsistent head rotations in two English text readers. In contrast, Lee[7] has described much larger stereotypical horizontal head movements in three Korean readers. These head movements increase in velocity and assist the gaze strategy as the text is repeatedly read. However, a confounding factor in the study by Lee was the use of a text width of 90°, much wider than would be encountered in most reading tasks. Consequently, the adaptation of head movements observed may be related only to the performance of a novel unnatural task.

It has recently been shown that head movements are suppressed during sequential looking tasks to optimize stable fixation.[8] It is possible that head movements contribute to the reading strategy by being suppressed to reduce the fixation instability that is caused by head movements.[9,10] To demonstrate suppression of head movements would require a much larger sample size than that used in previous studies to account for the wide variation in horizontal head movement propensity (size of head movement in relation to saccadic gaze shifts) in a normal population.[11,12]

Vertical head movements during reading have not been investigated at all. The vertical component of gaze may be particularly important in reading, because the vertical eye muscles control eye torsion. It is known that torsional disparities can occur during upgaze and downgaze while reading at close proximity.[13–15]

We present in this report the first systematic investigation into the characteristics of horizontal and vertical head movements during repeated performance of a standard reading task. We were interested to know whether suppression of head movement occurs during a standard reading task and so have compared the propensity for head movement during reading with the propensity for saccadic head movement in a large number of subjects ($n = 45$). We were also interested in whether adaptation of head movements assists in repeated performance of a standard reading task or whether it is a feature of reading unusually wide text widths. To do this, we compared results with the previous 90° text width used by Lee[7] with those obtained with a standard reading text width (A4 letter size).

Methods

Subjects

Fifteen young adults were included in the first part of the study, consisting of repeated reading of a standard A4 reading task and a 90° reading task (10 men and 5 women, mean age, 28.9 ± 7.4 years [SD]). In the second part of the study, comparing saccadic and reading head movement propensities, a further 30 subjects were recruited, bringing the study group to 45 subjects. The group comprised 24 men and 21 women (mean age, 48.8 ± 21.2 years), including 13 subjects aged

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between 18 and 30 years, 8 subjects between 30 and 45 years, 11 subjects between 45 and 65 years, and 13 subjects between 65 and 85 years. The older subjects were included in the study because of the larger saccadic head movement propensities in the elderly. In prior observations, we have found a significant increase in saccadic head gain with age of 0.068/decade ($P < 0.0001$; Proudlock FA, Shekhar H, Gottlob I, unpublished observations, 2003).

All subjects had full corrected visual acuity and normal stereoscopic vision and were free from any otologic or neurologic deficits other than presbyopia. Presbyopic subjects wore single near-vision lenses with a visual field in excess of 70° horizontal and 55° vertical. The study received local ethics committee approval and was performed with the subjects' consent after explanation of the nature and possible consequences of the study. The study was performed in accordance with tenets of the Declaration of Helsinki.

Recording

An infrared video pupil tracker (EyeLink eye tracker; SensoMotoric Instruments GmbH, Berlin, Germany) was used to record simultaneously the horizontal and vertical right and left eye positions and head position at a sample rate 250 Hz. (Technical specifications concerning the EyeLink system can be found at http://www.eyelinkinfo.com.) A detailed comparison of the eye-tracker system to the scleral search coil method has been previously reported.[16] By default, the eye tracker measures both eyes but only the data from the right eye were used in the study. The EyeLink eye tracker has a resolution of 0.005° and a noise level of less than 0.01° RMS (velocity noise <3deg/s RMS). The accuracy of the recordings for the gaze data was determined through a verification process performed by the eye tracker before each recording. The average error, maximum error, and offset (±SE) were 0.42° ± 0.057°, 0.87° ± 0.098°, and 0.68° ± 0.119°, respectively.

The pupil- and head-tracking cameras are mounted on a headband. The whole head-mounted apparatus weighs approximately 600 g. The pupil tracking cameras and mounts were positioned in the extreme peripheral visual field offering no obstruction to the subjects' effective field of view. Eye tracker recordings were converted into neurophysiological software system files (Spike2; Cambridge Electronic Design, Cambridge, UK). EyeLink uses custom cameras that do not have field timing or use averaging.

The eye data were calibrated with a series of nine fixation points, projected onto a rear projection screen of 1.75 m width and 1.17 m height, using a projection system (VisLab; SensoMotoric Instruments GmbH) and a video projector (resolution: 1024 × 768; CP-X958 LCD; Hitachi, Ltd., Tokyo, Japan). The subject sat at a distance of 1.2 m from the screen. The nine fixation points were projected individually in the shape of a 3 × 3 grid, 40° wide and 35° high. The calibration was repeated if the error for any point was more than 1°, or the average error for all points was greater than 0.5°. There is no drift in the EyeLink system, except from some slight movement of the headband that can take a few seconds to settle into position because of the viscoelastic properties of the skin. We performed a drift correction before each trial to compensate for this, which consisted of the subject's fixating a black spot displayed at the center of the display. The reported gaze position was used to correct any postcalibration drift errors. The linearity of the eye data was corrected for by the calibration.

Head position was derived from the same system with a series of four infrared markers placed around the rear projection screen, tracked with a camera mounted above the eyes. The manufacturer's specified head measurement range is ±30° for rotational movements and 36 cm for translational movements; however, the linearity of the head measurement depends on the visibility of all four infrared markers. The calibration of the head movement data was confirmed for each setup by pointing the head to a series of targets projected onto the rear projection screen by a laser pen mounted on the head. The targets covered a horizontal range of ±30° (in 10° steps) and a vertical range of ±25° (in 5° steps). The head data were linear within 0.02% for ±20° and within 5% for ±30°. The peak-to-peak noise amplitude of the head data was less than 0.05° over the measured range.

Head data derived from the EyeLink system are equivalent to the screen position where the head camera is pointing. The head position is set to zero at calibration. The horizontal and vertical coordinates of the head position were used to derive horizontal and vertical head angles relative to a point 120 cm in front of the screen center (the cyclopean eye position with zero head angle). This allows for head rotations to be described as a percentage of the gaze shift, which is also defined relative to this point. Consequently, head rotations are defined neither from an oculocentric axis (because this undergoes a translation movement) nor a craniocentric axis but in relation to their relative contribution to the gaze shift. Gaze data (as a screen coordinate) and eye data (as an angle) are generated directly by the eye tracker. Gaze, eye, and head data were all converted to the same unit (angle in degrees) with respect to the same reference point (the cyclopean eye position).

The EyeLink eye tracker uses an automatic saccadic detection algorithm based on a velocity threshold of 35 deg/s and an acceleration threshold of 9500 deg/s^2 (using the Euclidean sum of horizontal and vertical angles). A measure of two samples is used to derive velocity and a weighted sum of three samples to determine acceleration. The velocity threshold is raised by an average velocity computed for a period of 30 ms to prevent false triggering during smooth pursuit. The saccade detector becomes active if either the velocity or acceleration exceeds threshold. A saccade is defined as a period when the saccade detector is active for two or more samples in sequence and continues until the saccade detector is inactive for at least five samples. Blinks were replaced with a linear sequence of data connecting the points before and after the blink. The presence of a blink in the data was indicated with markers, to prevent incorrect analysis.

Protocol

Experiment 1. Fifteen subjects were instructed to read text printed on two different sizes of white card fixed at a standard reading distance of 33 cm. The first size was a standard reading format, A4 size (210 × 297 mm), with a text width of 170 mm and height of 247 mm, subtending a horizontal visual angle of approximately 28.6° width and 40.7° height. The second size of card covered a visual field similar to that used by Lee.[8] The card was 550 mm wide and 100 mm high, with a text width of 535 mm and height of 79 mm, equivalent to a visual angle of approximately 90° width and 13.5° height. This wider card was curved around the head to a radius of approximately 33 cm so that the text was equidistant from the eyes. Both sizes of card were printed with black single-spaced text of Times New Roman font, 12-point size—51 lines of text on the A4 card and 16 lines of text on the 90° card.

Two cards of each size were printed with the text of "Tom Thumb" and "Snow-drop" taken from the English translations of the Brothers Grimm fairy tales as used in the N6 and N8 pages of the *Moorfields Bar Reading Book*.[17] The subject first read the A4 and 90° texts once with different stories on each. The order of these two tasks was randomized. This was followed by the second reading of the A4 and 90° texts, with the two stories swapped. The order of these two tasks was also randomized. The subjects were instructed to read the text silently rather than aloud, because oral reading could introduce unwanted head movements.

Experiment 2. Reading and saccadic head movement propensities were compared in 45 subjects as the subjects read 25 lines of the A4 reading test. A horizontal saccades test was performed in which the subjects performed head-free gaze shifts to randomly mixed saccadic target jumps from 10° to 60° in 10° steps moving every 1.5 seconds projected onto the rear projection screen as described earlier. Forty-two saccadic gaze shifts were performed in all.

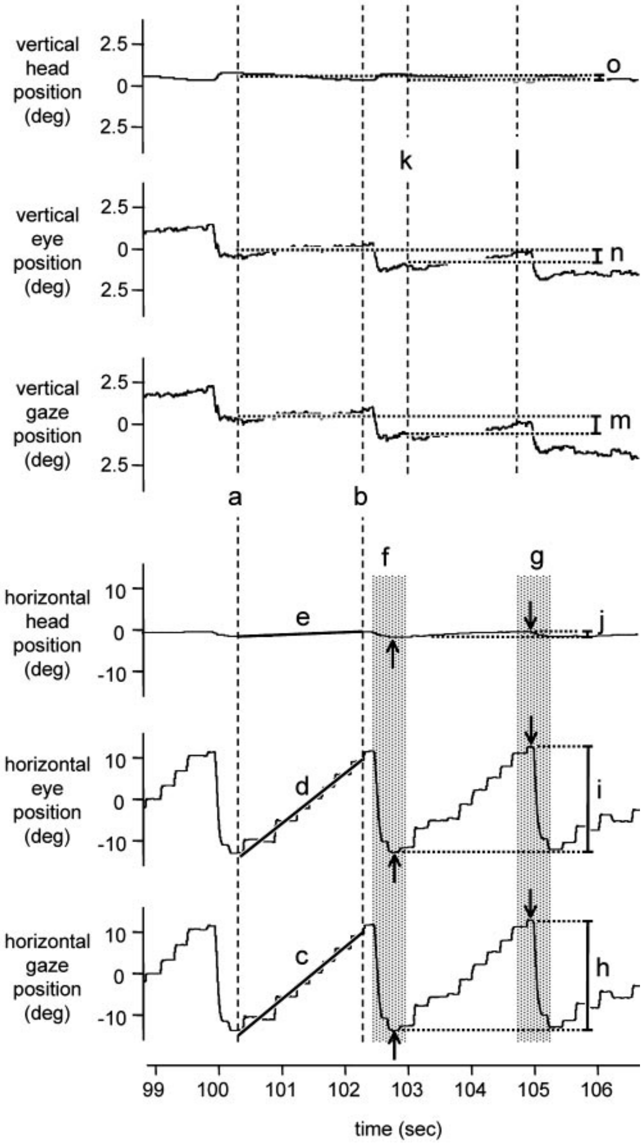

FIGURE 1. Method used to calculate amplitudes and velocities of gaze, eye, and head movements over each line read. Two cursors were positioned (a, b) to cover each line read, equivalent to the central 90% of range between the peak velocities of large leftward return saccades. Horizontal velocity was estimated using the best-fit line between the cursors for gaze (c), eye (d), and head (e) data. *Hatched regions*: range used to locate minimum (f) and maximum (g) horizontal excursions over the course of a line of text (*arrows*). This was equivalent to a time range of ±30% beyond the range between the cursors (excluding the range between the cursors). Differences between the minimum and maximum excursions were used as a measure of horizontal amplitudes of gaze (h), eye (i), and head (j). Vertical amplitude was measured from the difference between the means of vertical gaze (m), eye (n), and head (o) positions between the cursors for successive lines.

Analysis

Experiment 1. For the 90° reading test, 15 lines were analyzed, and 45 lines were analyzed from the A4 reading test (equivalent quantities of text). Figure 1 gives an example of the cursor positions (dashed lines) used to calculate horizontal and vertical amplitudes and horizontal velocities for gaze, eye, and head traces. Reading lines were identified from the large return saccades, which typically exceeded 250 deg/s gaze velocity in a leftward direction. Cursors were set within the central 90% of the large return saccades (Fig. 1, points a and b) so that the data between the cursors corresponded to a reading line. Raw traces of gaze, eye, and head were displayed to allow cursor positions to be modified where return saccades were below threshold (250 deg/s) or a double saccade occurred during the return movement.

Horizontal Velocities. Gaze (Fig. 1, point c), eye (d) and head velocities (e) for each line read were estimated from the slope of the best-fit line of the respective data between the cursors. Means were calculated for each subject.

Horizontal Amplitudes. The hatched region in Figure 1 indicates the range used to locate minimum (Fig. 1, point f) and maximum (g) horizontal excursions over the course of a line read (indicated with arrows). This was equivalent to a time range of ±30% beyond the range between the cursors (excluding the range between the cursors). Differences between the minimum and maximum excursion were used as a measure of horizontal amplitudes of gaze (h), eye (i), and head (j). Means were calculated for each subject.

Vertical Amplitudes. The mean vertical gaze (Fig. 1, point m), eye (n), and head (o) amplitudes were estimated from the mean vertical shift between lines. This was calculated by finding the mean gaze, eye, and head positions between the cursors for each line and measuring the differences between the data for successive lines. The vertical amplitude over a page was calculated by multiplying the mean by the number of lines read.

Vertical Velocities. Vertical velocity was not calculated, because it is equivalent to horizontal velocity for a fixed number of lines. Occasionally the subject made an inordinately large head movement because of repositioning, stretching, or scratching. These data were excluded from the analysis.

Experiment 2. Reading head-movement propensity (or head gain) was calculated for each subject from the mean head amplitude divided by the mean gaze amplitude calculated as described earlier. Saccadic head movement propensities were calculated by extracting data from the horizontal saccades test for gaze saccades to leftward and rightward targets of 20° and 30°. This was equivalent to the mean horizontal gaze shift when reading the A4 text (23.3°). The horizontal gaze, eye, and head positions were measured semiautomatically at points 500 ms before and 1000 ms after each target jump (Figs. 1, see cursors at points a and b). Gaze and head amplitudes were calculated for each target jump as the difference between the data measured at the two points. The points could be moved manually to avoid analyzing a blink or if the gaze or head movement was not stable at that point. The mean head amplitude during saccades was divided by the mean gaze amplitude to give head movement propensity for each subject.

Statistical Analysis

Paired samples *t*-tests, with Bonferroni correction for multiple testing, were used to determine significant differences between the first and second readings of A4 and 90° texts and the difference between saccadic and reading head movement propensities. The general linear model was used to look for significant trends over the time course of trials.

RESULTS

Experiment 1

Original traces of horizontal and vertical head, eye, and gaze positions are shown for one subject in Figure 2 for the A4 and 90° reading tests. All subjects demonstrated the characteristic pattern of gaze during reading of A4 text and 90° text consisting of a left-to-right staircase pattern of fixations and saccades as each line was read followed by a gaze shift from right to left to commence the reading of a new line. During the reading of A4 text, changes in horizontal eye position were almost identical with the pattern of gaze with only minimal horizontal head movements (Fig. 2A). In contrast, during the reading of 90° text, a large horizontal head movement occurred, causing

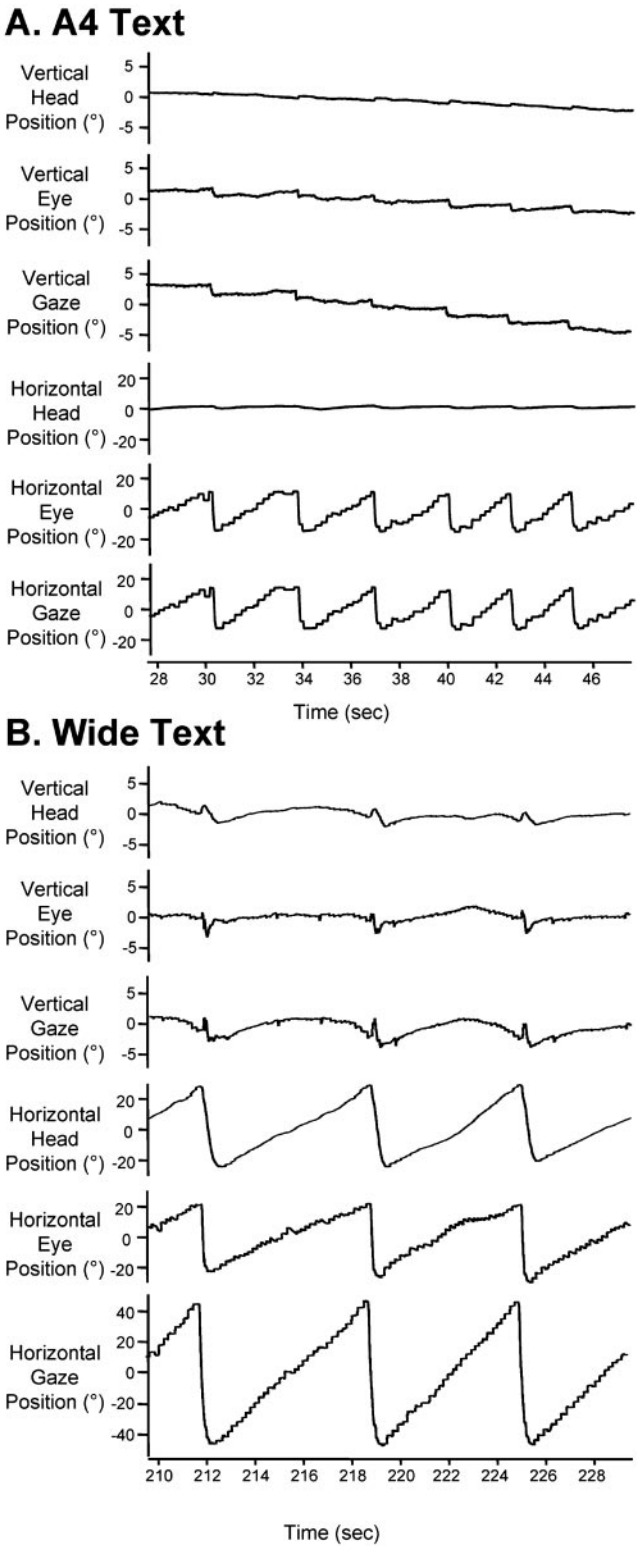

Figure 2. Original traces from a representative subject of horizontal and vertical gaze, eye, and head position data during the A4 and 90° reading tests generated from the infrared pupil and head tracker.

the amplitude of horizontal eye movements to be smaller than that of the gaze (Fig. 2B). The pattern of horizontal head movements during 90° text reading and in some subjects who made larger head movements during A4 reading invariably resembled the gaze pattern. This consisted of an approximately linear velocity movement from left to right followed by a rapid movement from right to left at the same time as the gaze shift to the next line. Vertical head-movement traces, although more variable and irregular than those for horizontal head movements, showed a steady downward movement over the whole course of a reading trial along with the gaze and eye traces (Figs. 2A, 2B, top three traces). A vertical deviation in gaze and head movements was usually evident during the large return saccades of the 90° reading test.

Plots of horizontal versus vertical gaze, eye, and head position are shown in Figure 3 for the same subject, obtained during the course of an A4 and 90° reading trial. The eye position plot for A4 reading (Fig. 3A) covered most of the page horizontally, but spanned only approximately half the page vertically. This was because a large head movement occurred during the course of reading the page, accounting for much of the vertical movement. In contrast, during 90° reading, the horizontal eye movement spanned only approximately half of the page, whereas, the horizontal head movement accounted for the rest of the movement (Fig. 3B).

The relative contribution of eye and head movements to the gaze excursions over the course of the A4 and 90° reading tasks are illustrated in Figure 4 for the 15 subjects. Means of the horizontal and vertical amplitudes for both the first and second trials are plotted (±2 SE). During A4 reading, mean vertical head amplitudes accounted for 28.7% (2.5%) of the gaze amplitude in contrast to the horizontal head amplitudes, which accounted for only 4.3% (0.6%) of the gaze. Mean horizontal head rotations were much larger during 90° text reading, equivalent to 40.3% (3.2%) of the horizontal gaze amplitude.

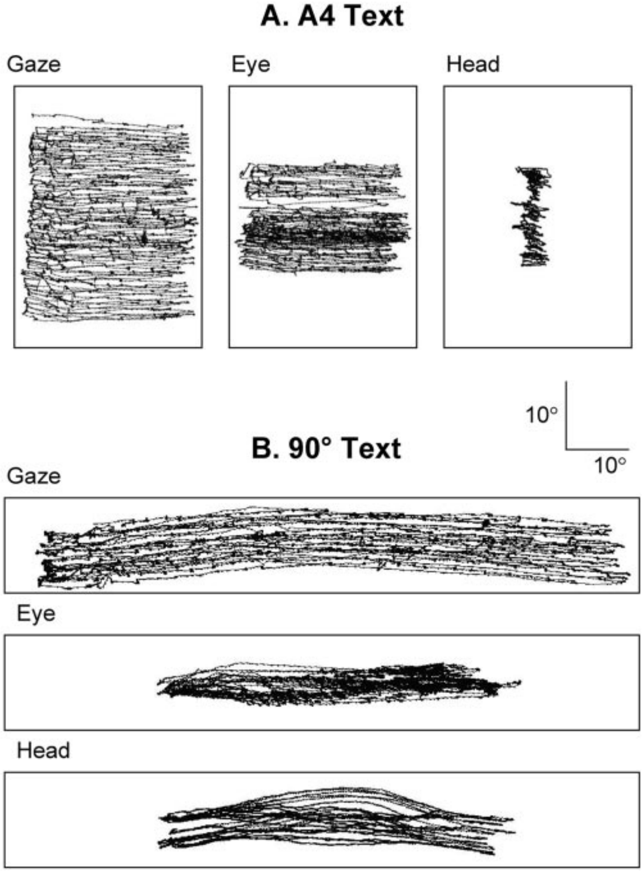

Figure 3. Horizontal versus vertical plots of the raw gaze, eye, and head position data during the (**A**) A4 and (**B**) 90° reading tasks, from the subject shown Figure 2.

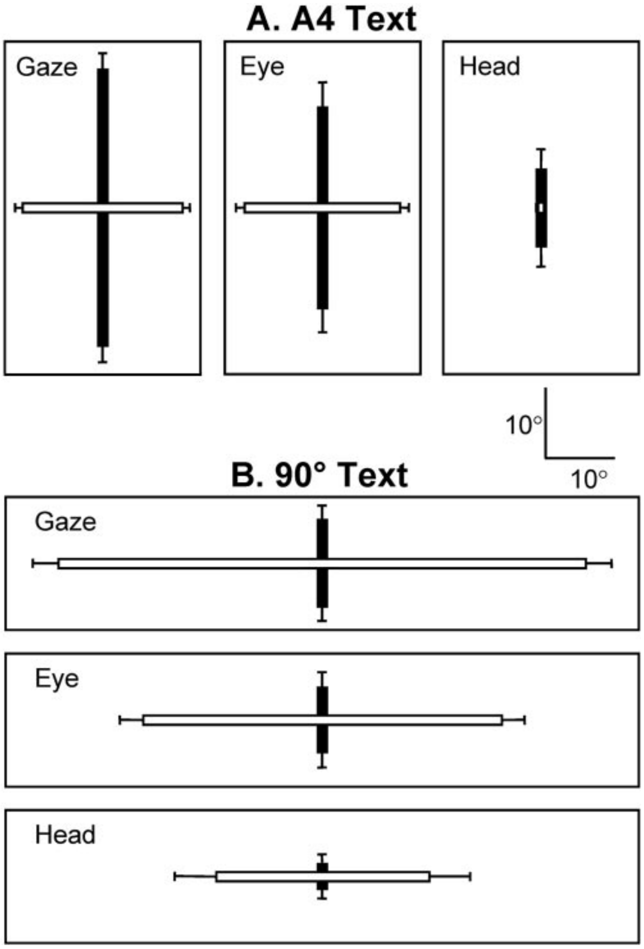

FIGURE 4. Mean (±2 SE) horizontal (□) and vertical (■) gaze, eye, and head amplitudes for all 15 subjects during the A4 text reading and 90° reading trials. The mean is given for the test and retest trials combined.

Mean vertical head movements were 28.4% (5.2%) of the vertical gaze amplitude during reading of 90° text reading. The mean horizontal and vertical gaze excursions for the A4 task were 23.3° (0.5°) and 40.6° (1.2°), respectively, whereas, mean horizontal and vertical gaze amplitudes for the 90° text reading trials were 76.8° (1.9°) and 12.6° (0.7°), respectively.

The consistency of any changes made by subjects when repeating the A4 or 90° reading tasks were illustrated by plotting data from the first reading against the second reading (Fig. 5). Mean horizontal amplitude (Figs. 5A, 5B) and velocity (Figs. 5C, 5D) were plotted for each line, as well as the mean vertical amplitude change between successive lines (Figs. 5E, 5F). Vertical velocity was not plotted, because it is equivalent to horizontal velocity for a fixed number of lines. Changes are evident when the data lie above or below the unity line (dashed line).

The mean horizontal amplitudes of head, eye, and gaze movements made over each line were close to the unity line for both the A4 and 90° reading tasks, indicating consistency between the two tasks (Figs. 5A, 5B). However, head amplitude data tended to lie above the line in both A4 and 90° wide reading trials (crosses) in contrast to gaze and eye data. Head movement amplitudes were significantly bigger in the second reading of A4 ($P < 0.001$) and 90° ($P < 0.05$) text, compared with the first reading.

Data for horizontal velocities of head, eye, and gaze movements made over each line all tended to lie above the unity line, indicating an increase in velocity on second reading of the A4 and 90° trials (Figs. 5C, 5D). The gaze velocity (equivalent to the reading speed) significantly increased for A4 ($P < 0.05$) and 90° ($P < 0.01$) text reading over the two trials. Head velocities also significantly increased on the second reading of A4 ($P < 0.0001$) and 90° ($P < 0.001$) text, compared with the first reading. However, there was no significant increase in eye velocity between the two trials of A4 and 90° text reading. Thus, the increase in gaze velocity was mostly due to an increase in head rather than eye velocity.

During the A4 task, horizontal eye amplitudes and velocities (Figs. 5A, 5C) were in close proximity to those for gaze (open squares), indicating that eye movements accounted for most of the gaze shifts during A4 reading. Means of head movement amplitudes were all below 2° and velocities were below 0.5 deg/s during A4 reading. However, during 90° text reading, horizontal gaze, eye, and head amplitudes and velocities (Figs. 5B, 5D) were clustered in distinct locations. Head movements accounted for approximately two fifths of the horizontal gaze amplitudes and velocities. The relative tightness of the mean values in Figures 5A–D indicate the consistency of the patterns

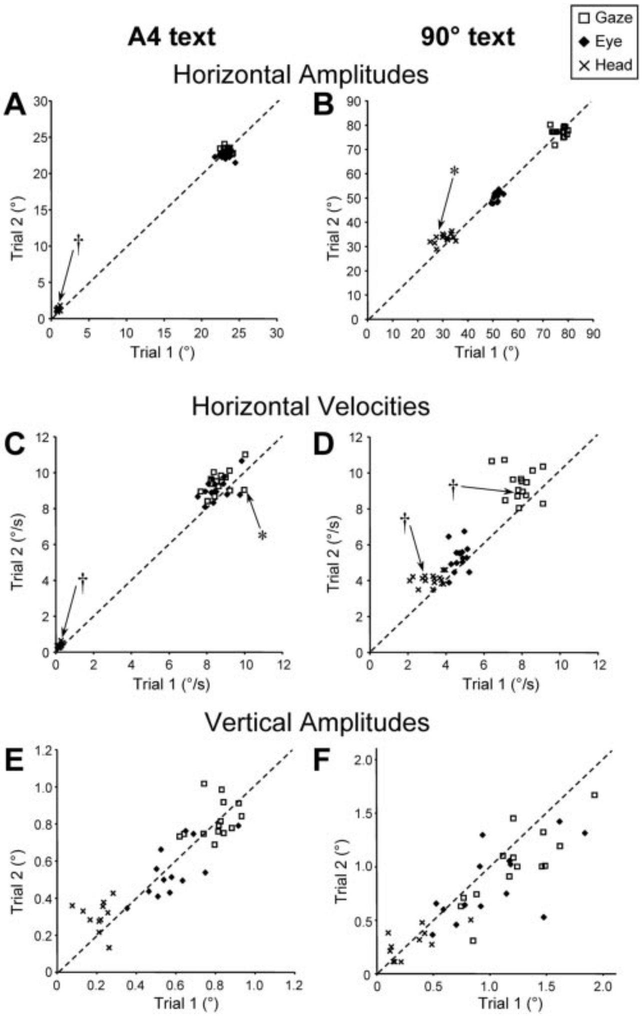

FIGURE 5. Plots of test against retest for A4 and 90° text reading trials for horizontal amplitude (**A**, **B**), horizontal velocity (**C**, **D**), and vertical amplitude (**E**, **F**). Mean data are displayed for each of the 15 subjects over the course of a line read. Vertical velocity was not plotted, because it is equivalent to horizontal velocity for a fixed number of lines. A significant difference between trial 1 and 2 are indicated with an *arrow* (*$P < 0.05$; †$P < 0.01$).

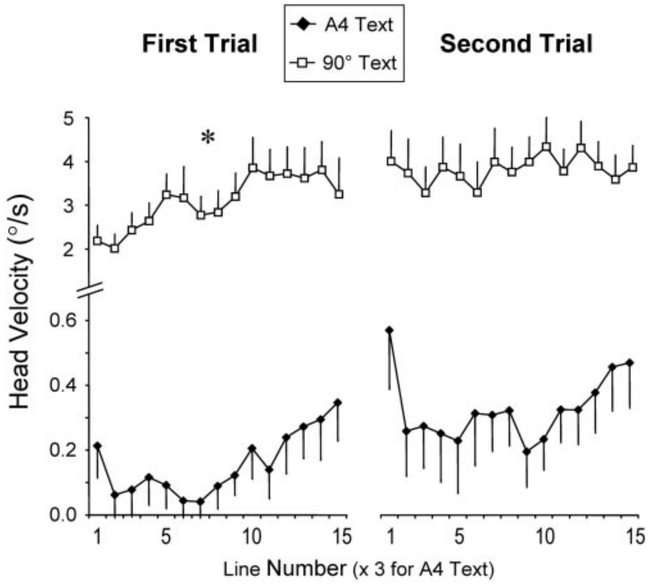

FIGURE 6. Mean velocity (±SE) of horizontal head movements in 15 subjects over the time course of first and second trials of A4 reading and 90° text reading. Each point is equivalent to the mean horizontal velocity for each line read during the 90° wide task, and an average of every three lines read during the A4 reading task. *Significant increase in velocity $P < 0.05$ (using the general linear model).

associated with A4 and 90° text reading in each of the 15 subjects for horizontal amplitudes and velocities.

Mean vertical head, eye, and gaze amplitude changes between successive lines (Figs. 5E, 5F) were less consistent between subjects than were horizontal amplitudes and velocities, particularly during wide reading. Vertical head movements during A4 reading (Fig. 5 E, crosses) tended to be above the unity line, however, these differences were not significant after Bonferroni correction.

Figure 6 shows the time course of changes in mean head velocity over the course of each trial. Each point is equivalent to the mean velocity for each line read during the 90° wide task and an average of every three lines read during the A4 reading task. The change in head velocity during the 90° wide text reading took place mostly during the first trial. In the second 90° text trial, the mean head velocity remained steady. A similar pattern was observed during A4 reading, although these changes were not significant. The head movements were approximately an order of magnitude slower in the A4 task than in the 90° reading task (see break in *y*-axis scale in Fig. 7).

Experiment 2

Head movement propensity during A4 reading was compared with head movement propensity during gaze saccades in 45 subjects (Fig. 7). Saccadic head movement propensities covered a wide range from 0 to 0.8. However, reading head movement propensities were all below 0.2, resulting in a regression line of the data (bold line) that was much more shallow (slope, 0.11) than a unity line of equal reading and saccadic head movement propensities (dashed line). The difference between reading and saccadic head movement propensity was highly significant ($P < 0.0000$).

DISCUSSION

A standard reading task (A4-sized English text) was associated with relatively small horizontal head movements, accounting for 4.7% of the gaze shift. Vertical head movements were much larger, accounting for 28.7% of the gaze shift when reading an A4 page. Reading of 90° wide text was associated with large horizontal head movements, accounting for 40.3% of the gaze shift. An increase in gaze velocity or reading speed was observed with increased task familiarity in both tasks, which is achieved in part by adaptation of horizontal head movements, which also increased significantly during both A4 and 90° reading. Head movement propensity was much smaller during an A4 reading than during a comparable saccadic gaze shift task.

Head Movements during a Standard A4 Reading Task

In our study, English readers consistently made horizontal head movements of a relatively small amplitude and velocity compared with gaze, during repeated reading of text from an A4-sized page. Kowler et al.[6] reported small head rotations (SD <1°) in two subjects during reading of 20.4° wide English text. However, in a given normal population, saccadic gaze shifts are associated with a wide variation in head movements,[11,12] which is not represented in a small sample size. We used a large sample size of 45 subjects to demonstrate that the wide variation in saccadic head movement propensity is not reflected in normal reading head movement propensity. This sample included 19 subjects older than 60 years, making use of the larger saccadic head movement propensity in older subjects (unpublished findings). All subjects made relatively small head movements when reading a standard sized A4 card of 12-point text. Stahl[12] has recently shown that when normal subjects perform saccadic gaze shifts up to ±50°, no head movements occur below a certain range of amplitudes. This eye-only range may vary in each subject, but beyond this range head movement amplitude increases proportionally with eccentricity. We have found that when subjects make significant head movements during reading, the pattern of the slow left-to-right movement is linear across the whole gaze shift and is not associated with a period of no head movement in the central portion of low eccentricity. This suggests that a different head movement control strategy is in operation during reading and the simple saccadic task.

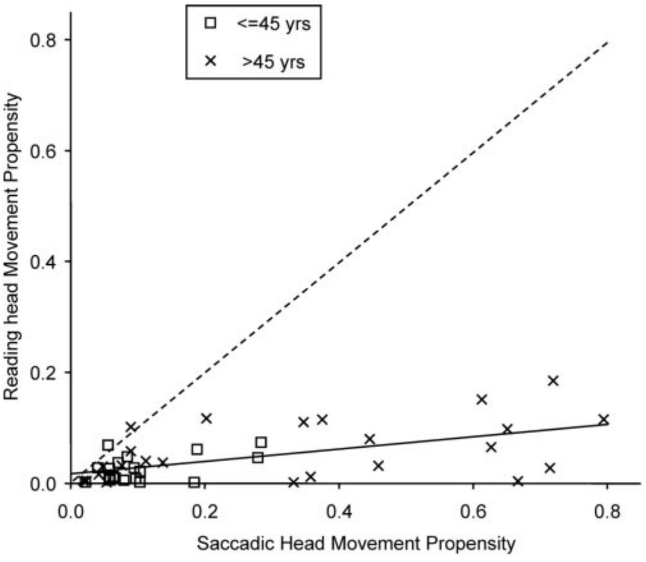

FIGURE 7. Plot of horizontal head movement propensity (head amplitude/gaze amplitude) during A4 text reading compared with an equivalent saccadic task (of 20° and 30° leftward and rightward target jumps). *Dashed line*: unity. *Solid line*: best fit of the data of all the subjects.

It has been shown that subjects unwittingly make slower and smaller amplitude head movements when stable fixation takes a higher priority during a sequential looking task,[8] because fixation instability worsens during voluntary and involuntary head movements, even though the vestibulo-ocular reflex provides some compensation for head movements.[9,10] It is possible that head movements are suppressed during a normal reading task because of the importance of stable fixation for reading.

In comparison to horizontal head movements, we found that relatively large vertical head movements were evident during an A4 reading task. Vertical head movements during reading have not been previously described. Although this may simply be a time-related phenomenon because a vertical head shift occurs over the whole page, whereas the horizontal shift repeats every line, it is possible that there are some explicit advantages to making vertical head movements during reading. Vilis[13] has noted that when a text is read at close proximity, torsional disparities can occur toward the top and bottom of a page due to rotation of Listing's plane.[14,15] It is possible that vertical head movements occur to reduce these torsional disparities. Vertical amplitude measures of head, eye, and gaze were less consistent than horizontal amplitudes, probably because of the large variation in vertical displacement over the course of each line read compared with the mean difference in amplitude between lines.

Head Movements during a 90° Wide Reading Task

The head movement patterns evident during 90° reading differed greatly from those witnessed during the standard A4-reading task, indicating that this paradigm, similar to that previously used by Lee,[7] does not generate head movement patterns representative of normal reading. Also, the adaptation of head movements during the 90° task took place primarily during the first reading of the text, indicating that it is more related to task familiarity than to text familiarity, as suggested by Lee. It is of interest, however, that head control strategy can be rapidly switched between these two paradigms. In the case of A4 reading, horizontal head movements are minimized, whereas, during 90° text reading, large horizontal head movements are made that increased in velocity with repeated reading. It is interesting that the increase in head velocity on repeated reading accounts for most of the increase in gaze velocity and indicates that head movements can be adapted to improve the efficiency of the gaze strategy developed for a novel task.

Adaptations in eye–head coordination strategy have been described in relation to a number of imposed visual, mechanical, or neural constraints or changes in task demands, such as reduced visual field,[18,19] reduced ocular motility,[4,5] inverted visual field,[20] reduced saccadic gain,[21] changes in head inertia,[22] auditory and visually generated saccades,[23–25] and manual demands of a task.[7,26] It has been recently shown that after loss of eye movements, due to congenital or acquired ophthalmoplegia or unilateral eye restriction, the patterns characteristic of eye movements can be transferred onto the head control system (Gottlob I, Proudlock FA, ARVO Abstract 3345, 2001).[4,5] This suggests a highly adaptable common control mechanism to the eye and head, which can be rapidly transferred onto either head or eye system.

It is emerging that eye and head movements can show remarkable flexibility with respect to the degree of dependent or independent activity. During certain tasks such as driving, head movements are highly predictable and move with the gaze shift pattern.[27] In contrast, head movement patterns can be completely unrelated to the pattern of gaze for example when used in communication and expression.[28] We have shown that, during reading, head movements can be rapidly switched from being either suppressed during A4 reading to assisting in the efficiency of task during 90° wide reading. Varying degrees of either synchronized or independent activity are also characteristic of movements of the two hands in accordance with the extraordinary range of tasks they can perform. This is mediated by corticomotoneuronal projections that transmit to the hand muscles flexible synergies that vary depending on the task.[29,30]

In conclusion, our results support the view that the head and eye movement system is a highly coupled but extremely flexible system capable of rapidly switching between widely different tasks. During A4 text reading, head movement suppression is observed, probably to stabilize gaze. In contrast, during a 90° wide reading task, large head movements are made that significantly increase in velocity to assist in achieving a desired gaze velocity.

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