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Jeroen B.J. Smeets · Mary M. Hayhoe
Dana H. Ballard

Goal-directed arm movements change eye-head coordination

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Abstract We compared the head movements accompanying gaze shifts while our subjects executed different manual operations, requiring gaze shifts of about 30°. The different tasks yielded different latencies between gaze shifts and hand movements, and different maximum velocities of the hand. These changes in eye-hand coordination had a clear effect on eye-head coordination: the latencies and maximum velocities of head and hand were correlated. The same correlation between movements of the head and hand was also found within a task. Therefore, the changes in eye-head coordination are not caused by changes in the strategy of the subjects. We conclude that head movements and saccades during gaze shifts are not based on the same command: head movements depend both on the actual saccade and on possible future gaze shifts.

Key words Head movements · Visuomotor coordination · Saccadic eye movement · Latencies · Human

Introduction

Saccadic eye movements are made to shift gaze from one interesting point towards another. These movements are generally accompanied by head movements in the same direction, even if the saccade ends far from the boundaries of the oculomotor range. The amplitude of these head movements is generally assumed to be a percentage of the amplitude of the saccade, and the head movements follow the saccade at some latency. The values of the percentage and the latency depend on the experimental conditions (reviewed, for example, by Jeannerod 1988; Fuller 1992), and vary between subjects (Bard et al. 1992).

This view is based mainly on studies in highly artificial laboratory conditions. Simple tasks in artificial laboratory conditions are well suited to studying basic mechanisms of neural control. However, when we use such experiments to study the interaction between control mechanisms, their results sometimes tell us more about the experimental constraints than about the control mechanisms we want to study (Steinman et al. 1990). Our approach is therefore to study humans who are performing natural tasks, having their attention focussed on the task, instead of on the variables we want to study. Using this approach, we can study aspects of the nervous system without the cognitive intervention which is present in laboratory experiments. In this study we investigated eye-head coordination while the eyes and head were moving in a natural way to gather information to manipulate blocks.

One of the explanations put forward to account for the different gains and latencies of the head movements during saccades in different experiments is that head movements can be amplified or suppressed by conscious effort. However, two recent studies concerning head movements during unconsciously made eye movements yielded different results. From a study of gaze shifts during driving, Land (1992) concluded that when the gaze was shifted unthinkingly, the eyes and head received the same command. On the other hand, using reading as a task in which the gaze was shifted unthinkingly, Kowler et al. (1992) found much less correlation between the movements of eye and head. Their results included reports of motion of eye and head in opposite directions. Similarly, Pelz et al. (1994) reported widely diverging trajectories for gaze and head for subjects moving blocks to copy a model configuration. Dissociation between eye and head was also found in a classical double-step experiment (Ron et al. 1993). What can explain these different

J.B.J. Smeets (✉)
Vakgroep Fysiologie, Erasmus Universiteit Rotterdam, Postbus 1738, NL-3000 DR Rotterdam, The Netherlands; Tel: +31104087565, fax: +31104367594, e-mail: smeets@ffg.eur.nl.

J.B.J. Smeets · D.H. Ballard
Computer Science Department, University of Rochester, New York, USA

M.M. Hayhoe
Center for Visual Science, University of Rochester, New York, USA

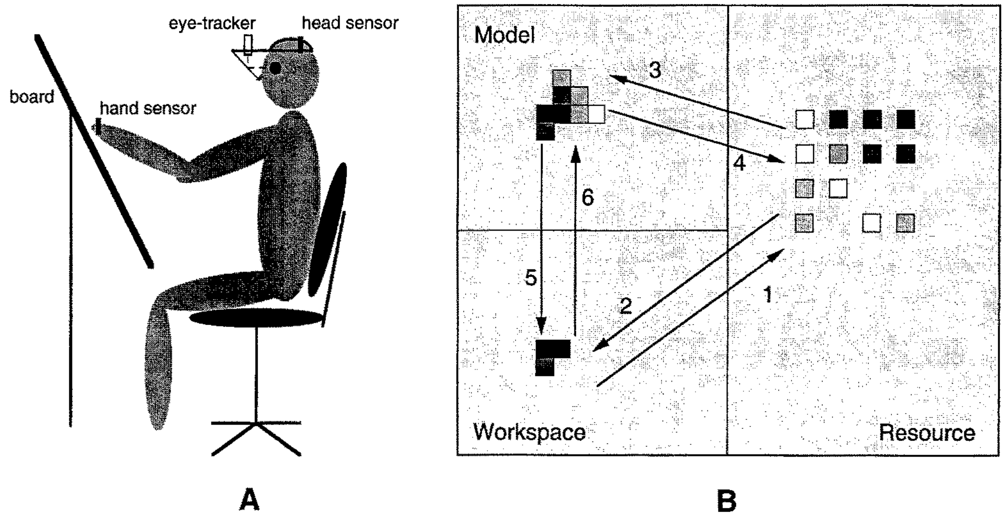

Fig. 1 **A** Side view of the experimental set-up. Subjects were totally free to position themselves as comfortably as possible. **B** The board with the three areas and the six types of saccades indicated. Three blocks have been moved from the resource to the workspace (a trial with instruction 1)

Table 1 The four instructions used in the experiment. Subjects were asked either to move their hand or their gaze in a particular pattern between the blocks in the three areas (*r* resource, *w* workspace, *m* model) of the board (Fig. 1)

Instruction	Hand movements	Hand manipulation	Gaze
1	r–w–r– ...	Pick and place the blocks	No instruction
2	r–w–r– ...	Touch the blocks	No instruction
3	m–r–w–m– ...	Touch the blocks	No instruction
4	None	None	m–r–w–m– ...

relations between eye and head found in different experiments?

To study whether differences in the gain and latency of head movements are due to (cognitively induced) changes in strategy, or due to specific requirements of the saccade, we carried out a set of experiments in which subjects were asked to perform manual tasks which required all their attention. We used the same task as Pelz et al. (1994) which revealed diverging trajectories for eye and head. The precise nature of the manual task was varied to induce changes in eye-hand coordination. These natural tasks were compared with a laboratory task requiring only gaze shifts of the same amplitude in exactly the same set-up as the natural tasks. It will be shown that these experimentally induced differences in eye-hand coordination yield differences in eye-head coordination.

Methods

Experimental procedure

Four colleagues from the University of Rochester volunteered as subjects in the experiment. They were familiar with the experimental set-up but were unaware of the exact purpose of the experiment.

The task of the subject was a variant of that used in the experiments of Pelz et al. (1994) and Ballard et al. (1995). In this paradigm, subjects were asked to copy a pattern of blocks (presented in a "model" area) in a "workspace" area, using blocks from a "resource" area. In the present experiment we used blocks of four different colours (Duplo), on a surface (oriented at about 20° to the vertical) in front of the subject (Fig. 1). Subjects sat in an adjustable chair at a comfortable height and distance from the board (about 50–60 cm). The model always consisted of eight adjacent blocks, with not more than four blocks of the same colour. Four blocks of each colour were stored in a four by four array in the resource. Gaze shifts between the three areas are about 30°, small enough to be made without any movement of the head.

To induce different patterns of eye-hand coordination, subjects received four different instructions (Table 1). The first instruction was to copy the model. For each block in the model, subjects had to pick a block from the resource and place it in the workspace. To investigate whether manipulation of the blocks had an effect on coordination, we used a second instruction in which the hand made the same movement as in instruction1 but did not pick up the blocks. Subjects were instructed to touch the blocks in the resource, and to touch the positions in the workspace where the blocks should be moved to. To change the correlation between the movements of the hand and the gaze, we used a third instruction. Subjects were instructed to touch a block in the model, touch a block of the same colour in the resource and touch its corresponding position in the workspace. In instruction 4, subjects were asked not to move their hand but to clearly fixate their gaze in the sequence of the hand movements of instruction 3. This last instruction resembles most the paradigms normally used to study eye-head coordination. In all instructions the sequence of movements had to be repeated for each of the eight blocks in the model area.

Each subject performed 16 trials, each with a different model and a different arrangement of the blocks in the resource. The model was covered with a black cloth until the trial started. The instructions were distributed randomly over the trials, counterbalanced between subjects. The subject received the instruction for a trial just before the start of that trial. At that moment, the subject was looking at a small fixation point on the cloth, keeping his hands on his lap.

Apparatus

Position and orientation of both the hand and the head were recorded using a three-dimensional electromagnetic system (The Flock of

Birds, Ascension Technology Corporation). Movements of the right hand were recorded using a sensor taped on the subject's thumb; movements of the head were recorded by a sensor mounted on a headband. The orientation of the left eye relative to the head was measured using an infrared camera-based eye-tracker (Applied Science Laboratories 4000SU), mounted on the same headband as the sensor for head position. The total mass of the headband, position sensor and eye-tracker was about 1.6 kg, corresponding to an inertia of about 0.02 kg m^2. The effect on head velocity of such an inertia is modest (Gauthier et al. 1986). Eye, head and hand trajectories were digitized at 60 Hz and stored on disk using software developed at the University of Rochester. Sometimes a frame was missed; these values were obtained off line by interpolation.

Data analysis

To compare the movements of hand, head and gaze, we transformed all measured positions and orientations to a position on the board. For the hand, this was done by projecting the hand position perpendicular to the board. For the head, we calculated (using the measured position and orientation of the head-sensor and an estimate of the position of the eye relative to this sensor) the point of intersection between the board and a line pointing straight ahead from the left eye. The gaze was expressed as the point of intersection between the board and the line of sight of the left eye (calculated using the position and orientation of the head and the orientation of the left eye relative to the head). After these transformations, the accuracy of the final measure (position on the board) was better than 1 cm.

Saccades[1] were detected using a velocity threshold of 1 m/s (about 100°/s). Using additional constraints for amplitude, starting position and end position, saccades were categorized as a gaze shift from one area of the board to another (six types: see Fig. 1) or excluded from further analysis. For each type of saccade in each trial, ensemble averages of the gaze, head and hand velocities between 300 ms before and 500 ms after the maximum velocity of the saccade were calculated. These ensemble averaged velocity profiles were used to determine the maximum velocity and the onset of the movements of head and hand. We will use the word "latency" to indicate the time difference between these movements and the onset of the saccade (a positive value means that the saccade leads).

In general, the head and hand were not stationary when a movement to a different part of the board started. To prevent too early detection of the onset, we used a very conservative threshold to detect the onset of head and hand movement: the moment the velocity surpassed 50% of its maximum value. For movements starting from a stationary situation, this was about 50 ms after the onset of movement. For the end of these movements a similar criterion was used: the first moment after the maximum velocity that the velocity fell below 50% of this value. The use of this method (combined with the increased inertia of the head) means that comparison of the values of the latencies between systems and with latencies reported in other studies is very difficult. However, changes in latencies for one system between conditions can be detected in this way. The results, presented in the following section to not depend critically on the precise definition of latency.

Our equipment did not allow a better time resolution than 16 ms for the collection of data. As the sampling is not time-locked to any event in the experiment, averaging of these inaccurate results will yield a more accurate result than the sampling interval. A simple thought-experiment with two conditions can illustrate this. Suppose we compare condition A, in which the head starts moving exactly 16 ms after the saccade, with condition B, in which this latency is 20 ms. The onset of the saccade will fall at a random position within a certain sample interval, which we call sample 0. As our sampling interval equals the latency of the head movement in condition A, the head movement will always start during the next sample (sample 1): a measured latency of 16 ms. In condition B, the sample in which the head movement will start depends on the position of the onset of the saccade within sample 0. The head movement will start in sample 1 (measured latency 16 ms) if the onset of the saccade is within the first 32–20=12 ms of sample 0 (75% of trials if they are randomly distributed). If the saccade starts during the last 4 ms of sample 0 (25% of the trials), head movement will start in sample 2 (measured latency 32 cm). For condition B we will find, therefore, an average measured latency of $0.75\times16+0.25\times32=20$ ms. Despite our initial resolution of ±18 ms, we can differentiate between 16 ms and 20 ms if we average many trials! Theoretically, the resolution in detecting average timing *differences* in the final result is the expected error in an individual measure divided by the square root of the number of trials. As all comparisons in this paper are based on more than 60 trials, we can (in principle) report timing *differences* at a resolution better than $\pm8/\sqrt{60}\approx\pm1$ ms.

[1] In this paper, we use the word "saccade" to describe movements of the gaze, not movement of the eye in the head.

Results

A typical example of part of an experimental trial is given in Fig. 2. The gaze shifts from the resource to the

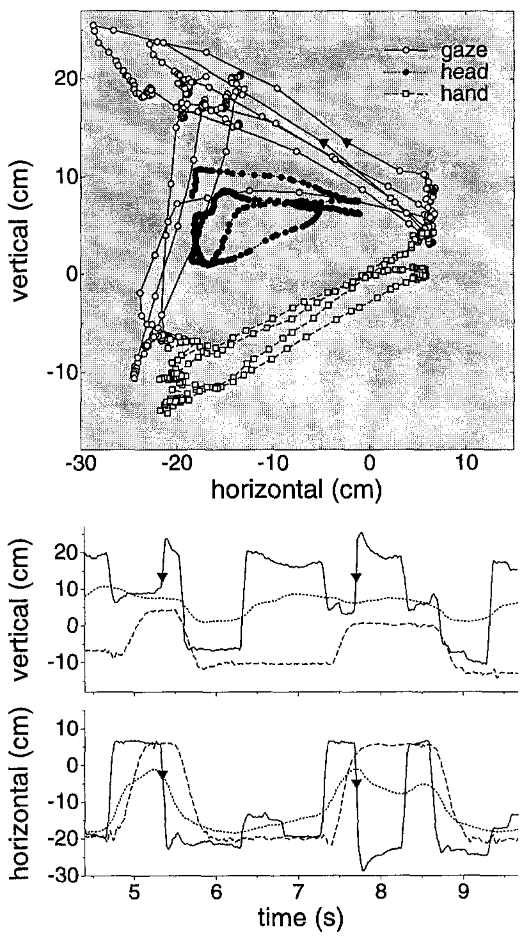

Fig. 2 Example of a part of a trial of subject KK, using instruction 2. *Upper part*: Trajectories of gaze, head and hand over the board. See Fig. 1 for the layout of the board. *Lower part*: The horizontal and vertical components of the movements as a function of time. Note the difference between the horizontal, leftward head movements at t=5.5 and t=7.8 (indicated by *downward-pointing triangles*). Although the gaze shifts are more or less the same, the absence of a hand movement after the latter saccade reduces the amplitude and increases the latency of the head movement

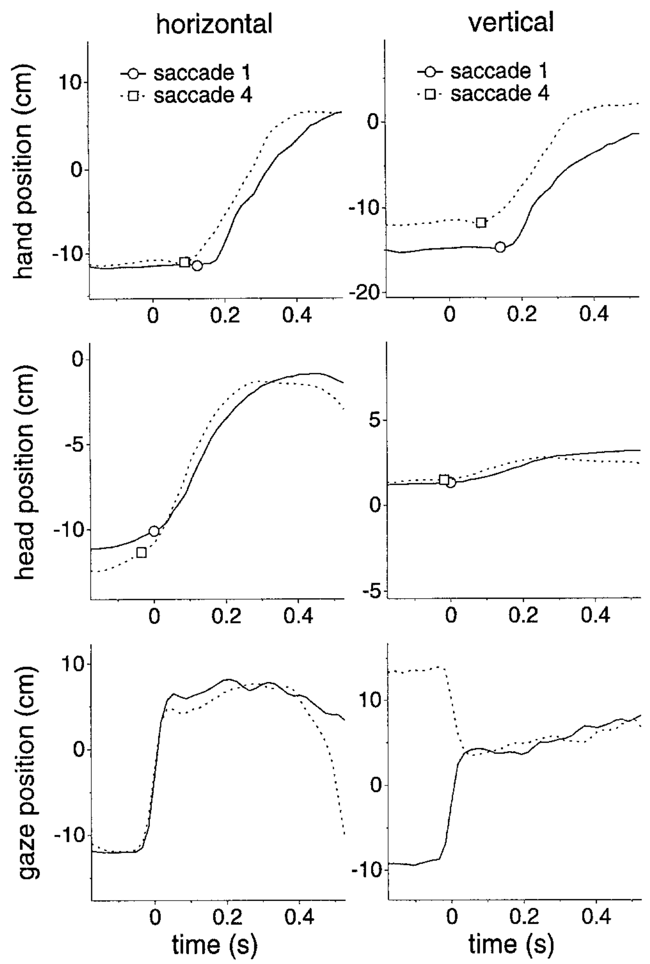

Fig. 3 Average profiles of saccades of types 1 and 4 of subject AF using instruction 1. The *symbols* on the curves of head and hand indicate the start of the movement, according to our definition in the text. Trials are aligned on the moment of maximum velocity of the saccade (t=0). The movements of both head and hand start for saccades of type 4 before those for saccades of type 1. Note that for saccades of type 4 both the head and hand move upwards, while the gaze shifts downwards

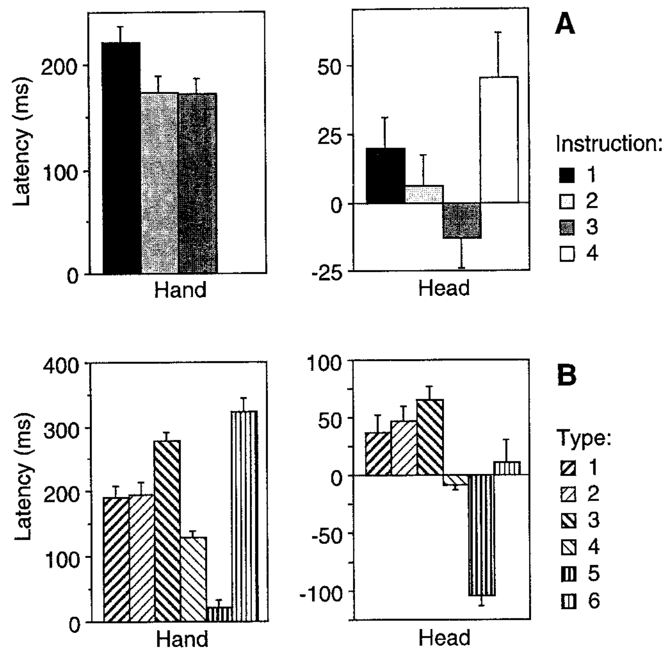

Fig. 4A, B Comparison between the latencies of the movements of head and hand, relative to the onset of the gaze saccade. *Error bars* indicate standard error of means. **A** The latencies of head and hand movements for the four instructions of Table 1, averaged over all types of saccades and all subjects. The instruction has a (rather small) effect on the latency of the hand. The same trend is also visible for the latency of the head. As instruction 4 did not include movements of the hand, no latency for the hand movement in this instruction is given. **B** The latencies of the head and hand movements for the 6 types of saccades (see Fig. 1), averaged over all saccades made by all subjects in instructions 1–3. The direction of the *hatching* indicates the direction of the saccade. The latencies of the hand movement depend strongly on the type of gaze shift. A similar dependence is found for the latency of the head movement

workspace and vice versa (to guide the arm movements) were almost always via the model (to check the position or colour of a block). The hand moved diagonally from the resource to the workspace and vice versa. The vertical components of the head movements were much smaller than the horizontal components. The horizontal movements of gaze, head and hand followed a coordinated pattern: a shift of gaze was followed by a movement of the head, which (in general) preceded the movement of the hand. The exact timing and amplitude of the head movement relative to the saccade depended on the movement of the hand. The example in Fig. 2 shows two saccades from the resource towards the model (filled triangles). The head movement was larger and had a shorter latency for the saccade which was followed by a hand movement.

To analyse the data further, we averaged the saccades for each type and subject. In Fig. 3 we compare the head and hand movements accompanying two types of saccades, both directed towards the resource for one subject under instruction 1. The horizontal components of these saccades were very similar, as were the movements of head and hand. However, there were some slight but important differences. The latency of both head and hand movements were shorter for the type 4 saccades than for the type 1 saccades. The vertical components of saccades of types 1 and 4 were in opposite directions. However, after both saccades the hand moves upward. The vertical component of the head follows the direction of the hand. The examples of Figs. 2 and 3 suggest that both the timing and the direction of the head movement correlate with the movement of the hand.

This correlation between the timing of head and hand was not accidental; it was found for all subjects and all instructions, as illustrated in Fig. 4. In Fig. 4A, one can see that the latency of the hand with respect to the saccade decreased from 240 ms in instruction 1 to 170 ms in instruction 3 (instruction 4 did not include hand movements). In trials in which the hand moved, the latency of the head (on average 10 ms) depended in a similar way on the instruction. However, when the subjects did not move their hand, the latency of the head was much larg-

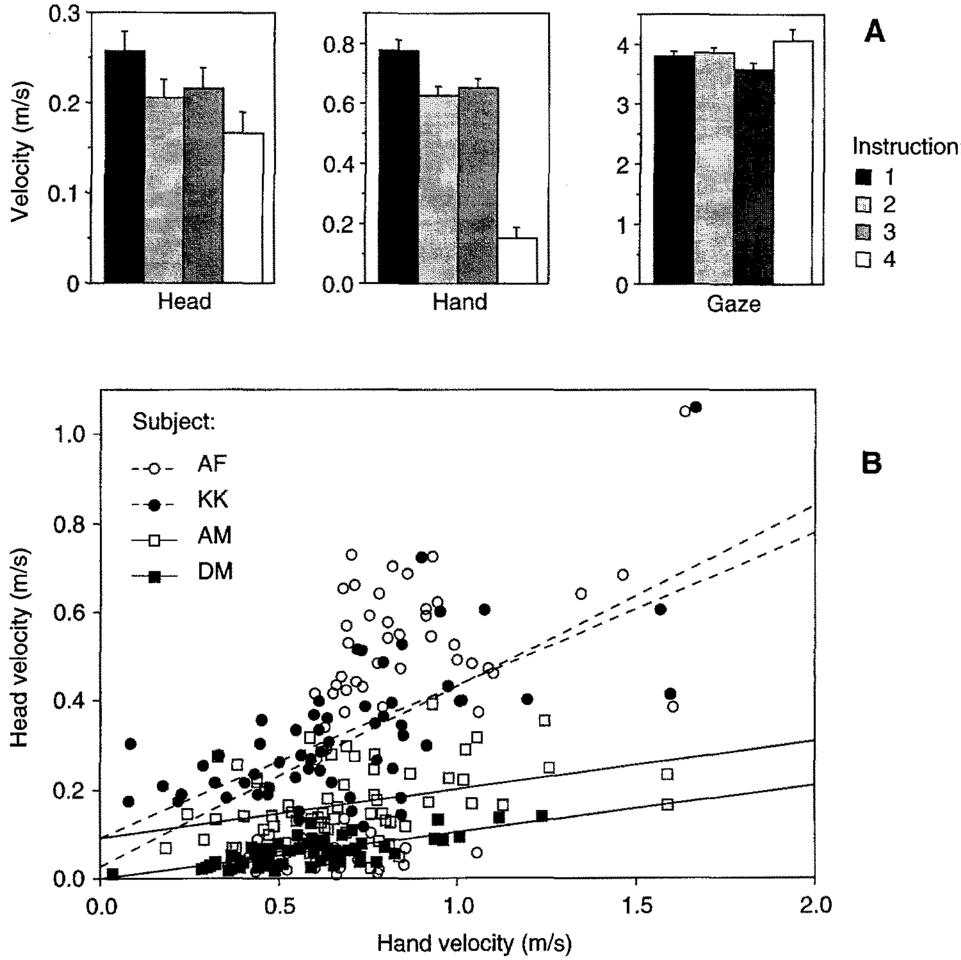

Fig. 5A, B The maximum velocities of head and hand compared. **A** The maximum velocity of head and hand for the four instructions of Table 1, averaged over all types of saccades and all subjects. **B** Scatterplot of the maximum velocity of the head as a function of the maximum velocity of the hand. Each *datapoint* is the maximum of the average velocity following a saccade of one type under one instruction of one subject. As instruction 4 did not include movements of the hand, no values of this instruction are used. Different *symbols* indicate different subjects: *squares* subjects with small head movements, *circles* subjects with large head movements. The *lines* are the regressions between the maximum velocities of head and hand for each subject

er: 50 ms. In Fig. 4B, we grouped the latencies of head and hand according to the type of saccade. For the primarily horizontal saccades (1–4), the horizontal components of hand and head movements showed a similar pattern of latencies: the shortest for saccades from model the resource, and the longest for saccades from resource to model. For the primarily vertical saccades, the latency of head and hand was shorter for the downward saccades than for the upward saccades. A two-way ANOVA (confidence level P=0.02) showed that both the instruction and the type saccade had a significant effect on the latency of the movements of both head and hand, without a significant interaction. The latencies of head and hand (of all saccades in all conditions) were significantly (P<0.05) correlated in three of our four subjects (on average: r=0.5, regression coefficient 0.43). The timings of the ends of the head and hand movements are also correlated within subjects, although with a smaller correlation coefficient (r=0.4) than their latencies. In conclusion, the timing of the movement of the head is clearly correlated with the timing of the hand movement.

The maximum velocities of both the horizontal (0.25 m/s) and vertical (0.10 m/s) head movements were independent of the type of saccade made. The maximum velocity of the head depended strongly on instruction and subject. In Fig. 5A, the maximum velocities of the head and hand are plotted for the four instructions. Both the head and the hand of our subjects reached their highest velocities in instruction 1, and had their lowest velocities in instruction 4. This correlation was not due to changes in the speed of the gaze shifts: instructions had no significant effect on the speed of the saccade. In Fig. 5B the maximum velocity of the head is plotted as a function of the maximum velocity of the hand. Each datapoint represents one type of saccade for one subject under one condition. Within each of our four subjects, the maximum velocities of head and hand (of all saccades in all conditions) were significantly (P<0.05) correlated (on average: r=0.6). The range of maximum velocities of the head movements varied strongly between subjects. Following Bard et al. (1992) we categorized them either as "head-movers" (AF, KK; regression coefficient 0.37) or as "non-head-movers" (AM, DM; regression coefficient 0.11).

Discussion

We described the movements of gaze, head and hand in several tasks. The gaze shifts were similar to those in the experiments in Ballard et al. (1992, 1995). The task was to move the hand and/or the gaze; head movements were not mentioned in the instructions, and were not necessary for completing the task. We therefore regard the movements of the head as dependent on the movements of hand and gaze. The main observation is that both the latency and the velocity of movements of the head depend not only on the gaze shift (as reported in many other studies) but also on the movements of the hand. Independent of whether the hand movement had a long latency due to the type of saccade or due to the task, it yielded a longer latency for the head movement relative to the gaze shift. The same holds for the maximum velocities of the head and hand. The correlation coefficients we found indicate that about 30% of the variation in the latency and velocity of head movements can be explained by variations in the latency and velocity of hand movements. This is a strong correlation, keeping in mind that many aspects of the task (like the distance between subject and board and the distances between the blocks) varied within and between trials.

The correlation between latencies is partly different from that reported by Bard et al. (1992). In a reaction time paradigm they found for some subjects (the head-movers) inversely correlated latencies of head and hand, while for the non-head-movers these latencies were correlated. Our results showed a positive correlation for all subjects. Carnahan and Marteniuk (1991) reported changes in relative latencies of gaze, head and hand when comparing pointing movements with different instructions. They suggested that the nervous system compensates for variations in the relative timing of the onset of movement by variations in speed, in order to keep the end of gaze, head and hand movements at constant relative latencies. This hypothesis is not supported by our results. For example, using the same instruction and subject, both the onset and the end of the hand and head movements of type 1 saccades have a longer latency than those of type 4 saccades (Fig. 3).

Vercher et al. (1994) put forward a similar hypothesis; they suggested that head and hand movements will end at the same time. From our data, it is not possible to obtain accurate estimates of the absolute latencies, so we cannot test their hypothesis directly. The hypothesis of Vercher and co-workers would predict better correlation between the end of the movements of head and hand than between their onset. Our experiment yielded a better correlation between the onset than the end of the movements. So the hypothesis of Vercher et al. does not help us to understand our results.

As differences in eye-head coordination occur also within one trial, differences in strategy between the four instructions cannot explain the effect of hand movements on eye-head coordination. In the rest of this section we will discuss our results in relation to several ideas about the reason for moving the head.

A first possible reason for making a head movement during a saccade is that it can make the gaze shift faster. This is important for visual guidance of the arm movement as it reduces the time during which visual acuity is low. Various pieces of experimental evidence support the view that head movements can indeed increase the maximum velocity of gaze saccades (see, for example, Laurutis and Robinson 1986). This argument, however, does not explain why the latency depends not only on the presence of an arm movement (experiment 4) but also on its latency (experiments 1–3). Moreover, our results (Fig. 5) show a (not significant) small but opposite effect of head movements on gaze velocity: the higher the head velocity, the lower the speed of the gaze shift. This difference between our results and those of other experiments is probably due to our instruction-free way of inducing different amounts of head movements, or due to the different relative timing of the movements of head and gaze. Increasing the speed of gaze saccades is thus not the reason for increasing the speed of the head movement in our experiment.

A second hypothesis to explain head movements during saccades is that humans need an eye orientation near straight ahead to know accurately what they are looking at (Biguer et al. 1984). In our task, accuracy demands were different for the three areas and the four tasks, so we have two predictions for this hypothesis. The first is that the latency of the head movement will be long for saccades directed towards the model (types 3 and 6: see Fig. 1), because these do not have to give accurate positional information for an arm movement. The head movements accompanying these saccades have indeed the longest horizontal (type 3) and vertical (type 6) latencies. The second prediction is that of a short latency of the head movement for an accurate task (instruction 1); this task, however, yielded the longest latencies. This hypothesis therefore cannot explain the variations in the relative timing of the head relative to the gaze.

Another type of explanation is based on the observation that two physically independent motor systems tend to move in phase (see, for example, Schöner and Kelso 1988). In our experiment, instruction 4 leads to an overt head movement with a latency of about 50 ms according to our definition. As our definition of latency overestimates by 50 ms (see Methods) and the movement of the head lags the electromyogram by about 100 ms (Biguer et al. 1982), this latency corresponds roughly to an activation of the muscles of the head 100 ms before those of the eye. By adding hand movements in instructions 1–3, we add an extra motor system (the hand) with latencies of about 200 ms, which corresponds roughly to an activation of the muscles of the hand 50 ms after those of the eye. If the extra motor system is to promote synchrony, it should lead to much longer latencies of the head movement. The addition of hand movement instructions 1–3, however, reduces the latencies of the head movement relative to those in instruction 4. This seems incompatible with this type of explanation.

The last type of explanation we wish to discuss is based on the realization that prediction of future system states is necessary for good eye-head coordination in gaze control (Brown 1990). Bizzi et al. (1971) reported that changes in the predictability of target position induce changes in eye-head coordination. In our task, the prediction of a future point of interest will change dramatically when goal-directed hand movements are introduced. The actual position of the hand is a likely candidate for a next gaze shift – for instance to guide manipulation of a block. If the head moves to facilitate gaze shifts towards predicted points of interest, its movements will therefore be correlated with hand movements. Following this argument, one would expect that the head movement would be correlated with both the gaze and the hand movements, both with a (small) lag. If one changes the argument slightly, so that the future position of the hand, rather than its actual position, is the likely candidate for the next gaze shift, then one can also explain our finding that movements of the head lead those of the hand by more than 150 ms.

We can thus explain our results by assuming that the characteristics of eye-head coordination depend not only on the requirements of the gaze shift itself but also on the predictions about what will be the next gaze shift. This line of reasoning explains also why Land (1992) found that the head followed the gaze perfectly. His subjects were scanning their field of view without a plan. Therefore, they did not have a predicted future point of interest, so the best the head could do was to follow the gaze shifts. In tasks in which the future points of interest are highly predictable (like reading), our hypothesis predicts a decoupling between gaze shifts and head movements, as reported by Kowler et al. (1992) and Pelz et al. (1994).

When there is only one target, eye and head will both move to that target. This does not mean that they received the same command at the same time. When using two targets with a very short delay (as done by Ron et al. 1993), or a static environment in which subjects can predict what the next target will be (as in reading or manipulating blocks), we see that head and eye can move to different targets. Thus, contrary to Land's (1992) conclusion, we conclude that even under circumstances where the gaze is shifted unthinkingly, eye and head can receive different commands at different times. These differences can be explained if we take into account the future points of interest.

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