Head movement control in visually guided tasks: postural goal and optimality

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Abstract

This work investigates the control of horizontal head movements in the context of unconstrained visually guided head and arm/finger aiming tasks. In a first experiment, the head was free to move while gaze was directed at randomly presented eccentric targets distributed horizontally (0 to 120°) at eye level. In a second experiment, the horizontal head orientation was constrained to predetermined positions (0, 15, 30, 45 or 60° rightward) while the right index finger aimed at targets with the arm fully extended. Kinematics of head movements in gaze displacements exhibits an initial component weakly correlated with target position, followed by multiple corrections. Since the eyes are assumed to already be aimed at the target when the corrections occur, it is suggested that one goal of head movement control is to achieve a desired final orientation (posture). This hypothesis is supported by results from the second experiment that reveal an association between eye/head orientation angles and errors exhibited in the visuo-spatial representation of the environment. The minimization of error then underlies the control of head movement as a postural response optimized for a given target and task condition.

Keywords

Vision, proprioception, sensorimotor system, motor control, motion prediction

1. Introduction

1.1. Control of head movement

The significance of head movements derives largely from the need to acquire visual information, which in turn is crucial for the calibration of human movement systems and interaction with the environment. The orientation and position of the head strongly affects the visual field. In particular, head mobility (±64°: [1]) can be used to enhance the effective range of the field of view beyond the mechanical range of motion (ROM) for the eyes (±55° for horizontal rotation: [2]), which makes the effective gaze range (= eye + head angle) cover up to ±119°. As the size of the peripheral visual field is ±90° [3], visual information can be effectively gathered over an entire range of ±180° from the mid-sagittal plane without moving the trunk or the whole body.

It has been reported that the angular distance the head contributes to gaze is typically smaller than target eccentricity [2], [4]–[6]), however the rationale for this limited displacement is not clearly explained. It was reported that the average functional ROM of the eyes, defined as the region within which the eyes are directed with a frequency of 90% for all head orientations, is ±22° (SD = 11.9°) [6]. Hence the functional ROM of the eyes is substantially smaller than the mechanical ROM, suggesting that head movement amplitude is controlled to maintain the eye within the functional range of motion and that this control is related to neural rather than mechanical processes.

1.2 Postural goal of movement control

One of the key questions of movement control concerns how the central nervous system (CNS) plans and generates the kinematics of goal-directed movements. A number of models have been developed that attempt to explain movement generation as an optimization process involving various cost functions, including jerk in the end-effector trajectories [7], joint torque changes [8], and joint effort [9], or a weighted sum of joint velocity [10],[11]. Typically in these models, the final end-effector position is constrained at the target position, and an optimization algorithm is used to determine the joint angles as functions of time that minimize the specified cost functions and resolve the redundant degrees of freedom.

Embodied in the constraint on the final end-effector position in the models noted above is an implicit assumption that the time-dependent changes in joint angles or the end-effector trajectories are the CNS's primary concern, while the final posture is simply the end outcome of joint movements. However, it has also been proposed that a predetermined final posture may be a goal that the CNS tries to achieve through movement [12],[13]. This viewpoint is supported by the observation that even when the target orientation is altered immediately before movement onset and the hand grasp trajectory undergoes a compensatory change, the final postures are equivalent for a given final target orientation [14]. Furthermore, the final posture and movement trajectories may be two independent domains over which separate adaptive controllers of the CNS act [15].

Since a posture can be defined as the set of joint angles describing the configuration of body segments, the relative contribution of the eye and head to gaze movements can also be understood as a postural response to a visual stimulus. Consequently it is of interest to determine whether the motor system responsible for controlling gaze is organized according to similar principles as the motor system responsible for controlling reaching/pointing movements. Specifically, the question to be addressed is whether final head orientation is merely an end outcome of the overall sequence of head movements, or the overall sequence of movement is generated in order to achieve a desired head orientation (= posture).

The way in which the CNS programs head movements to satisfy/achieve a final posture is largely unknown. Since head movements play an important role for the visual acquisition of targets of large eccentricity, accurate information about the target of large eccentricity may not be available before initiating a movement. Hence the CNS should make a plan of head movement to an "unknown" location. Resolution of this problem is likely to require an on-the-fly programming strategy that would give rise to kinematic features that differ from the preprogrammed time-optimal movements [16] generally observed when the targets are presented within the visual field [5],[17]. However, the temporal or geometrical organization of head movement kinematics has not been investigated for visual targets of large eccentricity.

1.3 Optimality of head posture

If a desired posture is what the CNS tries to achieve through movement, it may be because the final posture is an optimal set of joint angles for the given task requirements [14]. The CNS may store a repertoire of final postures that are updated and optimized through learning and experience [18]. The sets of movement representations can be retrieved and modified to generate new movements customized for a new context [19].

In general, it is still not clear how a final posture is optimized. In other words, the specific cost functions determining head posture for given task requirements have not yet been explicitly identified. In previous studies, the relative joint contributions to whole- or upper-body posture have been explained by an attempt to minimize a biomechanical cost such as torque [20], effort [21], fatigue [22],[23] or energy expenditure [24]. However, it is unlikely that these biomechanical processes would play a critical role in the determination of the head and eye posture, since moving the head, which is almost a hundred times heavier than the eyes, is not an economical solution. Thus it is suggested that the rationale to move the head even at a high physiological and kinetic “cost” is related to a neural, rather than a biomechanical issue.

An alternative explanation can be explored by investigating the degradation of hand pointing accuracy when the head movement is constrained or prevented, and the eyes have to move to an extreme position to achieve a desired gaze displacement [25]–[27]. In this case, it has been suggested that the postural response of the eye and head is optimized for target encoding and movement accuracy, which tends to degrade with increased eccentricity from the respective neutral position [26]–[28]. Hence, the optimal limb segment angles may be related to attempts by the CNS to minimize errors in the sensory representations of target and body segment positions.

One available model of eye and head orientation proposes that the contribution of the individual components should be optimized in such a way that the combined error (eye and head position) for egocentrically represented target position information is minimized [27]. The error defined in this model was based on the measurement of finger pointing positions. However, it is still not clear whether head orientation/displacement amplitude is necessarily associated with the *dispersion* or *variability* of the finger pointing position. Another limitation of this model is related to whether the control of the head movement can effectively be modeled from the measurement of finger *pointing/reaching* movements.

A number of studies have shown that the *undershoot* of finger pointing movements increases with target eccentricity [33]–[38]. Furthermore, vector-coded target representations [30],[39] and point-coded target representations [40] are expected to lead to different movement strategies. Since gaze movements are intended to align the foveal axis with the target, it could be assumed that head and eye movements are controlled using a vector-coded target representation, while finger reaching/pointing movements are based on a position-coded target representation. Hence, a new model based on the task requirements compatible with head movement control and rigorous parameterization is desired.

1.4 Aims and hypotheses of the study

1.4.1 Experiment I

Aims

1) Characterize the kinematics and strategy of unconstrained head movements used to locate visual targets of large eccentricity
2) Determine the relationship between the final orientation (posture) and movements in head movement control

Hypotheses

1) Head movements are composed of multiple components:
    - A pre-programmed initial movement is used to place gaze at an intermediate position estimated to be optimal for subsequent adjustments
    - Subsequent error corrections are based on proprioceptive feedback and updates in the representation of body segments
2) One of the goals of head movements is to achieve a desired orientation (= posture)

1.4.2 Experiment II

Aims

1) Measure hand aiming error in absence of visual feedback of the limb, as a function of head eccentricity in the torso and target eccentricity in the head

2) Determine the role of sensory motor error in the relative contributions of eye and head movements
3) Develop an empirical model describing head movement contribution based on error measurements and investigate the optimality of the final head posture in response to a visual target

<u>Hypotheses</u>

1) The head movement contribution can be determined by the minimization of the unweighted sum of two types of errors:
   - The error in encoding target eccentricity with respect to the head aiming direction (= eye-in-the-head angles, assuming that gaze is on the target) increases with target eccentricity
   - The error in encoding head-aiming direction increases with head eccentricity (head-in-the-torso angle)
2) Head posture is optimized to improve/enhance the accuracy of subsequent movements

2. Methods

2.1 Subjects

Five males and five females participated in the experiments as paid volunteers. They were students from the University of Michigan recruited through in-class advertisements or email announcements. The mean age of the participants was 22.3 years old (SD: 1.8); all were right-handed, free from any known musculoskeletal or neurological disorders, and had normal vision (20/20 or better) without corrective lenses. Mean stature and body weight were 170.9 cm (SD: 12.0) and 67.2 kg (SD: 16.3), respectively.

2.2 Experimental setup

Visual targets were placed on a horizontal arc (radius = 115 cm, arc length = 300 cm) in front of the subject. The elevation of the target arc was set at the individual seated eye level (Fig. 1). The visual targets were distributed either every 10° up to a maximum azimuth of 120° (Experiment I; Fig. 1a) or every 15° up to a maximum azimuth of 150° (Experiment II; Fig. 1b) of visual angle in the right hemisphere from the mid-sagittal plane. Each visual target was composed of alphanumeric characters (0 – 9, A, C, E, F, H, L, U, or P) displayed on seven-segment LED's whose visual angle was approximately 0.25°.

The subject was seated throughout the experiments. The seat position and arc height was adjusted so that the center of the display coincided with the center of the rotation of the head (atlanto-occipital joint). In the initial posture, the nasion aimed at the 0° target location. The room was either dimly lit (Experiment I) or completely dark (Experiment II) during the experiment.

< Fig. 1 about here>

An electromagnetic motion capture system (Flock of Birds™, Ascension Technology) with five sensors that measure movements with six degrees of freedom was used to record torso, upper extremity, and head movements. In Experiment II, a splint was wrapped to the right index finger to eliminate finger mobility throughout the experiments, so that the coordinates of the sensor placed on the dorsal side of the right hand could be used to estimate the fingertip position.

The movements of all landmarks were recorded at a 25Hz sampling frequency, and the trajectory of each landmark was smoothed in an off-line process using a zero phase shift second order Butterworth low-pass filter with a 6Hz cutoff frequency. The Cartesian coordinates and orientations of the sensors were used to estimate the joint center locations [41].

2.3 Procedure

2.3.1 Experiment I

For each trial, the subject was asked to look at the initial home display, located in the sagittal plane, until it disappeared (duration = 1 s), and then redirect gaze to an eccentric target illuminated for 2 s. Home and target display illuminations were accompanied by 100 ms distinct tones of 500Hz and 2000Hz, respectively. The subject was asked to fixate the illuminated display until the tone signaled the appearance of the next display (either home or target). It was required to read aloud each illuminated visual display. The head was free to move. No specific instructions regarding head movements were provided.

A trial was composed of the sequential occurrence of a home and a target presentation, and each subject performed a total of 24 trials (12 target eccentricities × 2 replications). The target locations were randomized and balanced across subjects.

2.3.2 Experiment II

The subject was initially seated in a reference posture, with the head aligned with the torso in the mid-sagittal plane. The head was then horizontally rotated to set the naso-occipital axis azimuth at either 0 (forward), 15, 30, 45 or 60° (rightward) for each block (Fig. 1b). A dental impression bar attached to a fixed frame was used to secure the head orientation during the trials, while the torso was secured to the chair with a harness. Training trials were performed until the experimental protocol became familiar. In each trial, the subject was asked to look at and read aloud the initial fixation display (duration = 2 seconds) aligned with the naso-occipital axis. A target, whose eccentricity was randomly chosen from 15 to 90° azimuth, was then displayed for 2 seconds. The subject was asked to redirect the eye gaze and to read the illuminated target display aloud until it disappeared. The illumination of the initial fixation and the eccentric targets was accompanied by a 100 ms tone at 500Hz or 2000Hz, respectively. The rate of change of displayed alphanumeric characters for both the initial fixation and eccentric targets was set to one per second. Once the eccentric target was turned off, the subject was asked to extend the right arm horizontally and aim as accurately as possible with the right index finger at the remembered position of the target. Once the finger-aiming direction was perceived as being close enough to the target, the subject depressed a button switch held in the left hand. Two seconds after the button depression, a 100 ms audio tone at 500Hz signaled to return the right hand to the initial position (on the right lap). A 5 second rest period separated consecutive trials.

A trial consisted of the presentation of a home and target display followed by the aiming task. A block was composed of twenty-four trials (6 target eccentricities $\times$ 4 replications). The target locations were randomized and balanced within each block. Each subject performed a total of four blocks, each of which corresponded to one of the four head azimuths. A rest period of 5 minutes was provided between each block. The order of blocks was balanced and randomized across subjects.

The procedures were reviewed and approved by the University of Michigan Health Sciences Institutional Review Board for compliance with the appropriate guidelines, state and federal regulations.

2.4 Data Analysis

In Experiment I, the independent variable was the target eccentricity expressed as the angle of the target from the mid-sagittal plane (+: rightward). The dependent variable was the azimuth of the head-aiming vector from the mid-sagittal plane (+: rightward rotation). The head-aiming vector was defined as the projection onto the horizontal plane of the vector from the head center of rotation (atlanto-occipital joint) to the nasion.

In Experiment II, the independent variables were the head-in-the-torso angle (θ_{head}) and the eye-in-the-head angle (θ_{eye}). The head-in-the-torso angle (= head aiming azimuth) was measured by the azimuth of the initial fixation offset with respect to the mid-sagittal plane (+: rightward rotation). Although eye gaze directions were not measured, it was assumed that the eye was fixating the target at the time of gaze completion, since the visual angle of a target was very small (< 0.25°) and the subject was required to read the displayed character changing intermittently. The eye-in-the-head angle (= eye aiming azimuth) was measured by target eccentricity with respect to head-aiming azimuth. The dependent variable was the magnitude of the angular error between finger aiming direction and target direction (Fig. 1b). The finger aiming direction was defined as the projection onto the horizontal plane of the vector from the atlanto-occipital joint to the tip of the right index finger, while the target direction was defined as the projection onto the horizontal plane of the vector from the atlanto-occipital joint to the target center. The included angle between the two projected vectors was used to measure the error magnitude, and a positive error value denoted an undershoot.

3. Results

3.1 Experiment I

The head movement contributing to gaze was composed of an initial fast transition followed by multiple corrective sub-movements (thin lines in Fig. 2a). The first acceleration phase appears to be common to all movements (thick line in Fig. 2a). In order to estimate the magnitude of the intended first movement component (truncated by subsequent subcomponents) it is of interest to recover the whole velocity profile by numerically reconstructing the deceleration phase (dotted line in Fig. 2b) using a mirror-flipped acceleration profile. The recovery process is based on the assumption that the non-truncated initial phase of the movement has the symmetric velocity profile of a preprogrammed movement, in spite of some variability [5],[42].

The following procedures were applied to reconstruct each initially intended head movement (IIHM) component (Fig. 2b). First, the completion of the initial acceleration phase was determined by the occurrence of the first zero crossing of the first order time derivative of head angular velocity. Second, based on the assumption that the identified initial acceleration phase corresponds to the initial half of a sigmoidal curve, the three parameters of a least-square fitting (mode position, dispersion, and scaling factor) were estimated. The timings for movement initiation, peak velocity, and completion were then estimated from the sigmoidal curve. Third, the head orientation in a global reference frame was represented by a time-dependent quaternion. Then the head-aiming direction at the end of the reconstructed velocity profile was estimated by extrapolation, knowing the head orientation at movement initiation and peak velocity. Specifically, the extrapolation process used a spherical linear interpolation of quaternions [43] by assigning 0.0 of normalized movement time to the head orientation at movement initiation, 0.5 to the peak velocity timing, and by estimating the head orientation at instant 1.0 of the normalized movement time (1).

$$\mathbf{s}(t;\mathbf{q}_i,\mathbf{q}_f) = \mathbf{q}_i(\mathbf{q}_i^{-1}\,\mathbf{q}_f)^t \qquad (1)$$

where **s**: quaternion representation of an interpolated (or extrapolated) head orientation

t: normalized movement time for interpolation (or extrapolation)

$\mathbf{q}_i$, $\mathbf{q}_f$: quaternion representations of the initial and final head orientation, respectively

< Fig. 2 about here>

The reconstructed velocity profiles indicate that the amplitude of the IIHM increases with target eccentricity, and reaches an asymptotic value (Fig. 3). This relationship was modeled using an exponential curve as in (2).

$$\hat{y} = b_1\left(1-\exp\left(-\frac{x}{b_2}\right)\right) \qquad (2)$$

where x: target eccentricity

$\hat{y}$: estimated amplitude of IIHM

b_1, b_2: model parameters estimated by least-square fitting

< Fig. 3 about here >

The estimated model coefficients for each subject are listed in Table 1. The mean asymptote (b_1) value is 20.3° with a standard deviation of 3.9° for all subjects, which indicates that the maximum amplitudes of the IIHMs do not exceed 20.3° for target eccentricity up to 120°.

< Table 1 about here >

It was observed that although the number of corrective sub-movements following the initial component increases with target eccentricity, the overall kinematics of corrective sub-movements shows a large variability (Fig. 2a). Furthermore, the average amplitude of the final head azimuth, which is equivalent to the head movement contribution ratio (HMCR) to gaze displacement, corresponds to 72% (SD: 0.04%) of target eccentricity.

3.2 Experiment II

The overall mean of finger aiming error across all subjects was +8.21° (SD 7.07°), which indicates a significant undershoot tendency (t-test $p < 0.01$). The ANOVA for combined subjects' data identified significant effects of the head-in-the-torso angle (head azimuth; $p < 0.01$) and the eye-in-the-head angle (target eccentricity; $p < 0.01$) on the magnitude of the error. Specifically, the aiming error increases with both head azimuth and target eccentricity. However, a chi-square test indicated that the dispersion of the aiming error for replicated trials does not vary significantly with either head azimuth or target eccentricity. Based on these findings a second-order polynomial regression model (3) was made to describe the finger aiming error as a function of head azimuth and target eccentricity for each subject.

$$\hat{\varepsilon}\left(\theta_{eye}, \theta_{head}\right) = \beta_1 + \beta_2\theta_{eye}^2 + \beta_3\theta_{head}^2 \quad (3)$$

where $\hat{\varepsilon}$: predicted aiming error

θ_{eye}, θ_{head} : eye and head direction, respectively

β_1, β_2, β_3: least-square fit coefficients

Overall, the adjusted R^2 of the aiming error model ranged between 0.86 and 0.17 ($p < 0.01$ for all subjects). The least-square fit coefficients (β_2 and β_3) indicate that for eight subjects the eye-in-the-head angle (θ_{eye}) contributes more than the than head-in-the-torso angle (θ_{head}) to the finger aiming error ($\beta_2 > \beta_3$), while the opposite is observed for two subjects (Table 2). A surface plot of the model (Fig. 4) indicates that the aiming error is the smallest when both the eye and head respective azimuths are close to 0° (neutral position), and increases with deviation from neutral.

< Table 2 about here >

< Fig. 4 about here >

A quadratic optimization model, whose objective function is to minimize the unweighted sum of errors associated with head-in-the-torso (head azimuth) angles and eye-in-the-head (target eccentricity), was developed to predict the optimal set of head and eye contribution for a given target eccentricity.

The objective function that minimizes the finger aiming error (ε) can be defined as follows (4):

<u>Objective</u>: Find $\boldsymbol{\theta}^* = (\theta^*_{eye}, \theta^*_{head})$ such that $\varepsilon(\boldsymbol{\theta})$ can be minimized

$$\min_{\boldsymbol{\theta}} \varepsilon(\boldsymbol{\theta}) = \beta_1 + \beta_2\theta_{eye}^2 + \beta_3\theta_{head}^2 \qquad (4)$$

<u>Subject to</u>:

$$\theta_{head} + \theta_{eye} = \theta_{target} \qquad (5)$$

$$lb(\theta_{eye}) < \theta_{eye} < ub(\theta_{eye}) \qquad (6)$$

$$lb(\theta_{head}) < \theta_{head} < ub(\theta_{head})$$

where $lb(\theta_i)$ and $ub(\theta_i)$ are the lower and upper bounds of segment i angle (θ_i) imposed by the respective range of motion.

The first constraint (5) indicates that the direction of gaze should be on the target at the time of gaze completion. The constraints represented in (6) indicate that both eye and head angles should be within their respective range of motion. A sequential quadratic programming method was used to solve the constrained nonlinear optimization problem [44]. Specifically, the number of eye-head azimuth combinations that satisfies the constraint in (5) should be first restricted by the range of motion constraints. The restricted sets of angle combinations (feasible solutions) are then evaluated for the associated error function ($\varepsilon(\boldsymbol{\theta})$) in order to find the optimal combination that minimizes the error ($\boldsymbol{\theta}^*$). This model is illustrated in Fig. 5 by an example.

< Fig. 5 about here >

In this context, the optimization model predicts that head orientation would be approximately 60% of target eccentricity on average, which is in reasonably good agreement with the measured head movement contribution ratio (HMCR) of 72% for horizontal head rotations measured in Experiment I. In addition, the model-predicted HMCR's are positively correlated with the HMCR's measured from individual subjects (Pearson's r = 0.65; Fig. 6).

< Fig. 6 about here >

4. Discussion

4.1 Multiple components in head movement kinematics

Investigation of head movement kinematics in Experiment I indicated that these movements are composed of a truncated fast component followed by multiple corrections. The reconstructed velocity profile of the initial component showed that the intended amplitude of this truncated component increases with target eccentricity and quite rapidly reaches an asymptotic value of approximately 20°. This feed-forward transition movement, most likely based on a cognitive mapping of the space in the absence of knowledge of the exact location of the target to be reached, seems to be generated to bring the head to a location that would allow the eye to reach a range within which the target may be expected to lie.

When foveal acquisition of the target occurs, its location can be estimated and corrective movements based on proprioceptive feedback are initiated to place the head in a specific location proportional to target eccentricity [4]–[6]. Although the number of corrective movements increases with target eccentricity in general, the overall kinematics of corrective movements shows a large variability. Hence it is suggested that a gaze displacement and the associated head movement, particularly in unconstrained conditions, are achieved through a number of kinematic variations that are loosely programmed using an on-the-fly strategy.

4.2 Postural goal of head movement control

From the perspectives of previous studies [25],[45]–[47], it is estimated that gaze is aimed at the target by the time the corrective head movements take place. In effect, these corrections should be unnecessary, since gaze is already aligned with the target direction. As the movement is not constrained in time, the secondary adjustments may be produced to compensate for a conservative underestimation of the head movement and reduce the cost of initiating a fast large head movement that would otherwise be truncated. Head inertia is not negligible, and it has been shown that the peak acceleration and velocity of head movement decrease if head inertia is increased [48],[49]. Consequently it is proposed that the goal of head movement control may include the achievement of a certain combination of eye and head orientation, or posture, with regard to target position.

It should be noted that the desired posture is achieved through an entire process involving an initial component and multiple subsequent corrections. This strategy may not appear to be an efficient way to achieve the movement goal, since the CNS may still pursue the desired posture from the movement onset by setting the desired body segment angles directly, as suggested by an equilibrium point hypothesis [12],[50]. However, the CNS does not know precisely where the target is before foveation; accordingly, the desired final head posture can be selected only after the execution of the initial component of head movement. Furthermore, it is suggested that each corrective movement may be used for successive evaluation of the state of the head/neck movement system, which may enhance the accuracy of the head position representation. Therefore, the course of the multiple corrections can be viewed as fine-tuning of the posture by updating the egocentric representation of target position and task space.

4.3 Posture as an optimal joint configuration

If one of the goals of head movement control is to achieve a predetermined posture, determined by both neural and mechanical factors, it can be assumed that a head posture is an outcome of optimization for the given task requirements and system constraints as tested in Experiment II. The optimal head posture within a context can be derived from a cost function related to the sensorimotor errors of the eye and head systems. In the present case, the finger aiming error increased in a quadratic manner with both the eye-in-the-head angle and head-in-the-torso angle. Consequently these results support that finger-aiming error is related to the respective deviations from the neutral position of the eye and the head, and thus these results support the hypothesis that the postural response of the head reflects an optimal solution for redundant degrees of freedom in terms of the accuracy of task space representation in an egocentric reference frame.

The proposed model attempts to explain the possible optimality of the head-eye postural response by the reduction in *undershoot* error of finger *aiming* movements (3D vector coding in a spherical coordinate system). In contrast, a similar model [27] based on *dispersion* of finger *pointing* movements (2D point-coding in a Cartesian coordinate system) yielded a predicted HMCR of 90%. The model proposed in the present study indicates that the predicted HMCR was approximately 60% on average, which is in good agreement with previous studies (65 – 75%: [2], [4]). In addition, the present model shows a remarkably good individual correlation with the HMCR measured in Experiment I.

The accuracy of an egocentric reference frame is important if subsequent visuo-manual tasks are to be executed after the target is located, since it is necessary to transform the represented body segment configuration and task space into a corresponding joint reference frame. Hence, a minimal visuo-spatial representation error within the initial reference frame is crucial since the transformation would not only transfer but also exacerbate the error, and further deteriorate the movement accuracy [52]. The accuracy of the target localization task is accordingly the most important criterion in controlling the head and gaze movements. This issue is also important from both application and theoretical perspectives, since visuo-spatial calibration, which is determined by head orientation, could critically influence the performance of subsequent hand movements generated to interact with the localized target.

5. Summary

Unconstrained gaze-driven head movements are composed of a truncated feed-forward type fast component followed by multiple feedback corrections. The reconstructed velocity profile of the initial component shows that the intended amplitude of this component increases with target eccentricity and rapidly reaches an asymptotic value of approximately 20°. When foveal acquisition of the target occurs, its location can be estimated and then corrective movements based on proprioceptive feedback are initiated to place the head in a specific location. These corrections would otherwise be unnecessary, since gaze is already aligned with the target direction. Consequently, the results support the hypothesis that achieving the final posture is one of the goals of head movement control. A cost function related to the sensorimotor errors of the eye and head systems was used to explain a possible optimality in the final head posture necessary to improve the accuracy of subsequent aiming movements represented in an egocentric reference frame.

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Summary

Head movement control in visually guided tasks: postural goal and optimality

by

K. Han Kim, R. Brent Gillespie, Bernard J. Martin

Unconstrained gaze-driven head movements are composed of a truncated feed-forward type fast component followed by multiple feedback corrections. The reconstructed velocity profile of the initial component shows that the intended amplitude of this component increases with target eccentricity and rapidly reaches an asymptotic value of approximately 20°. When foveal acquisition of the target occurs, its location can be estimated and then corrective movements based on proprioceptive feedback are initiated to place the head in a specific location. These corrections would otherwise be unnecessary, since gaze is already aligned with the target direction. Consequently, the results support the hypothesis that achieving the final posture is one of the goals of head movement control. A cost function related to the sensorimotor errors of the eye and head systems was used to explain a possible optimality in the final head posture necessary to improve the accuracy of subsequent aiming movements represented in an egocentric reference frame.

Figure Captions

Fig. 1 a) Configuration of the target arc for the gaze displacement task (Experiment I). b) Finger aiming task and definition of aiming error (Experiment II). A positive error indicates an undershoot.

Fig. 2 Superimposed head velocity profiles from a representative subject (a) and the reconstruction of an initially intended head movement component using a spherical linear interpolation method (b).

Fig. 3. Estimated amplitudes of initially intended head movement components. Data from a representative subject.

Fig. 4. Surface plot of the model prediction of finger aiming error as a function of head azimuth and target eccentricity. Data points for negative target eccentricities are estimated by mirror-flipping directions (for illustration purpose only). Model fit to data from a representative subject.

Fig. 5. Schematic of the minimum-error optimization problem for a target eccentricity of 60°.

Fig. 6. Correlation between the actual (Experiment I) and predicted (Experiment II) head movement contribution ratios (HMCR).

Figure 1

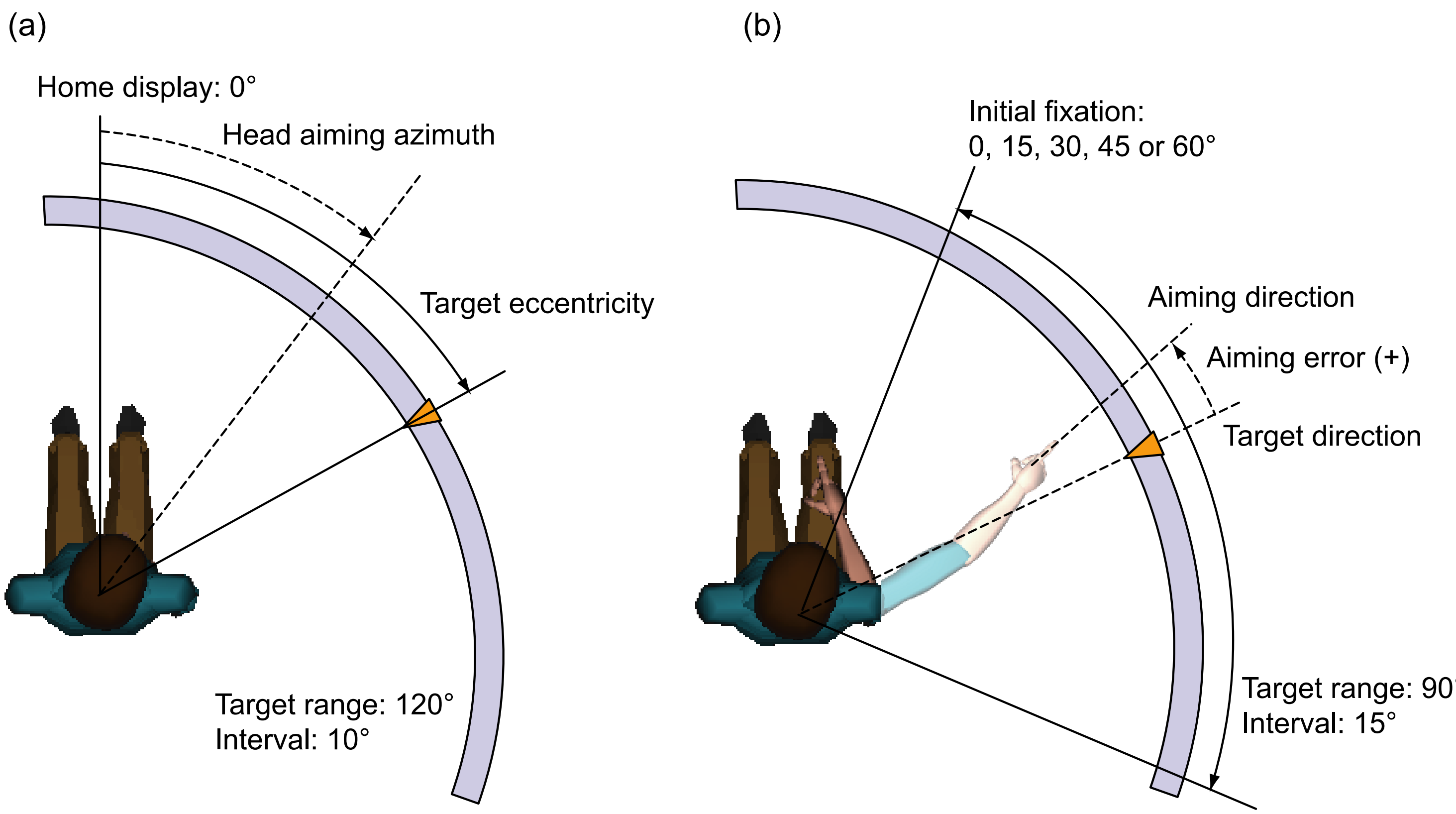
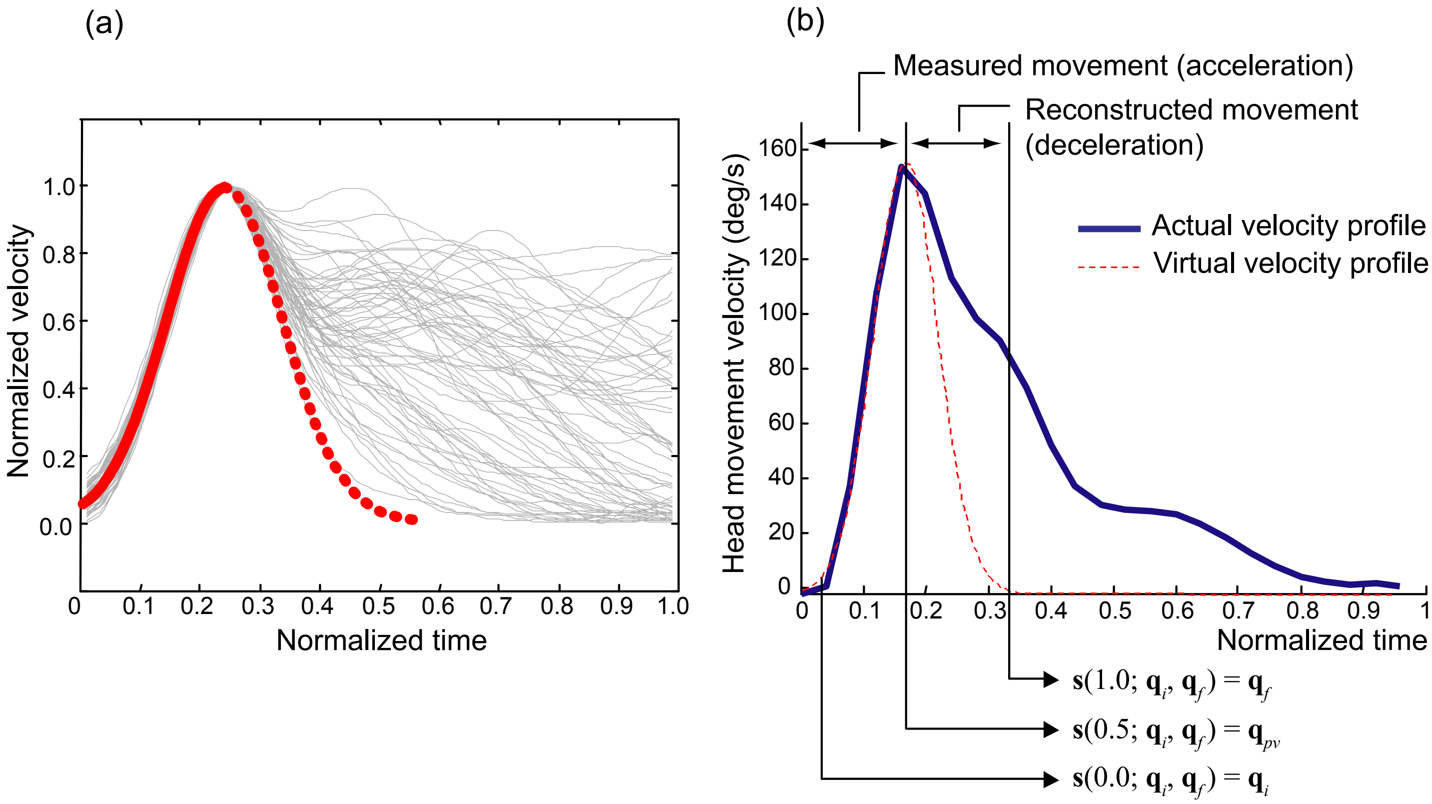
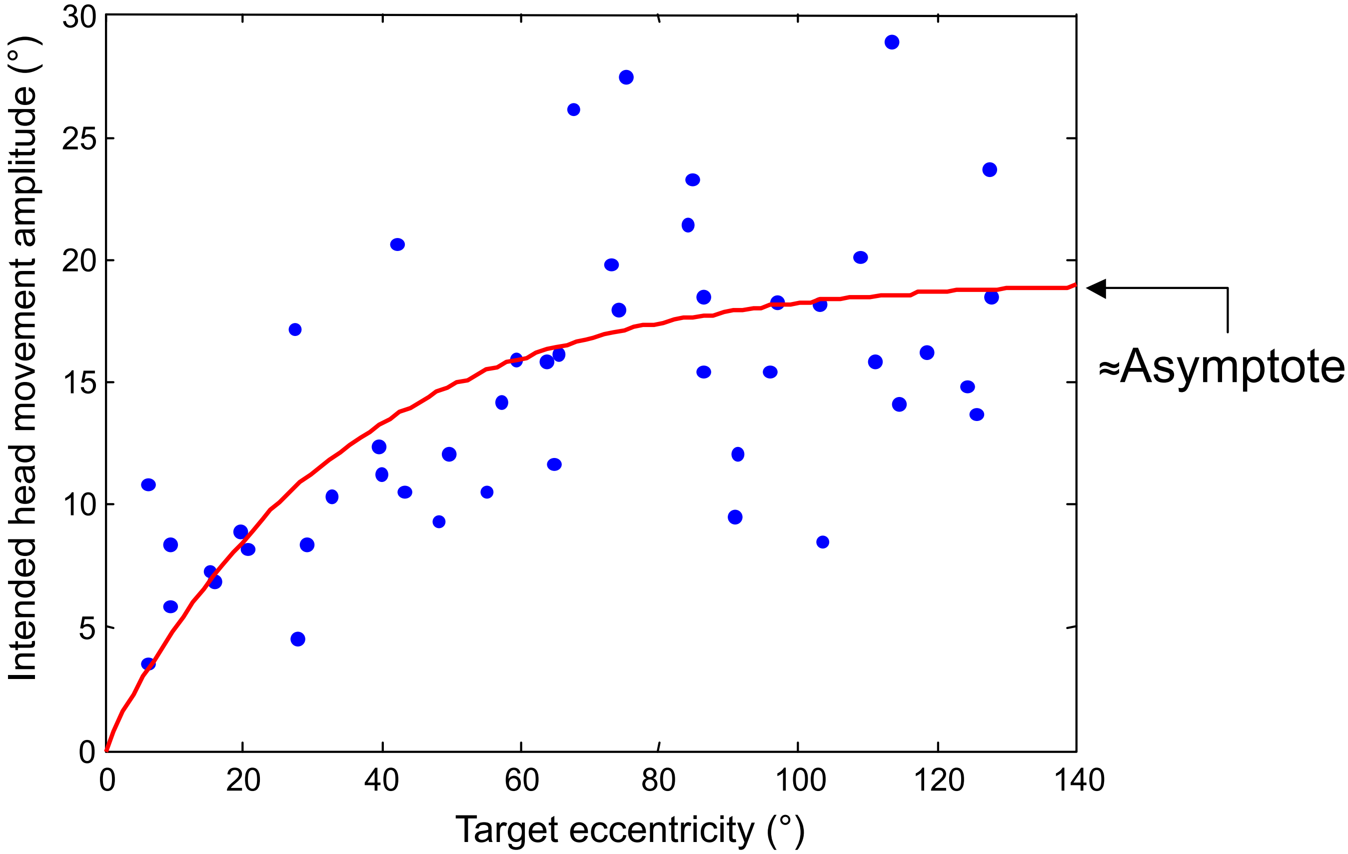

(a)
Home display: 0°
Head aiming azimuth
Target eccentricity
Target range: 120°
Interval: 10°
(b)
Initial fixation:
0, 15, 30, 45 or 60°
Aiming direction
Aiming error (+)
Target direction
Target range: 90°
Interval: 15°

Figure 2



(a)
Normalized velocity
1.0
0.8
0.6
0.4
0.2
0.0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Normalized time
(b)
Measured movement (acceleration)
Reconstructed movement
(deceleration)
Head movement velocity (deg/s)
160
140
120
100
80
60
40
20
0
Actual velocity profile
Virtual velocity profile
Normalized time
s(1.0; q_i, q_f) = q_f
s(0.5; q_i, q_f) = q_pv
s(0.0; q_i, q_f) = q_i

Figure 3



30
25
20
15
10
5
0
Intended head movement amplitude (°)
0
20
40
60
80
100
120
140
Target eccentricity (°)
≈Asymptote

Figure 4

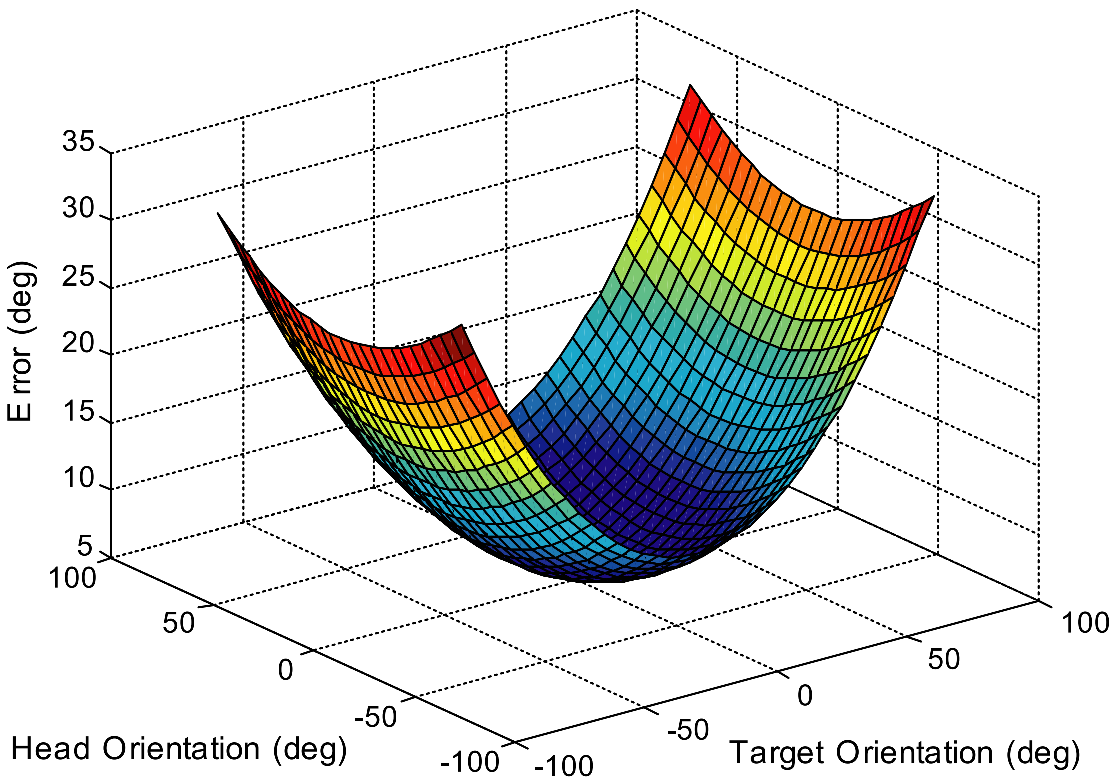
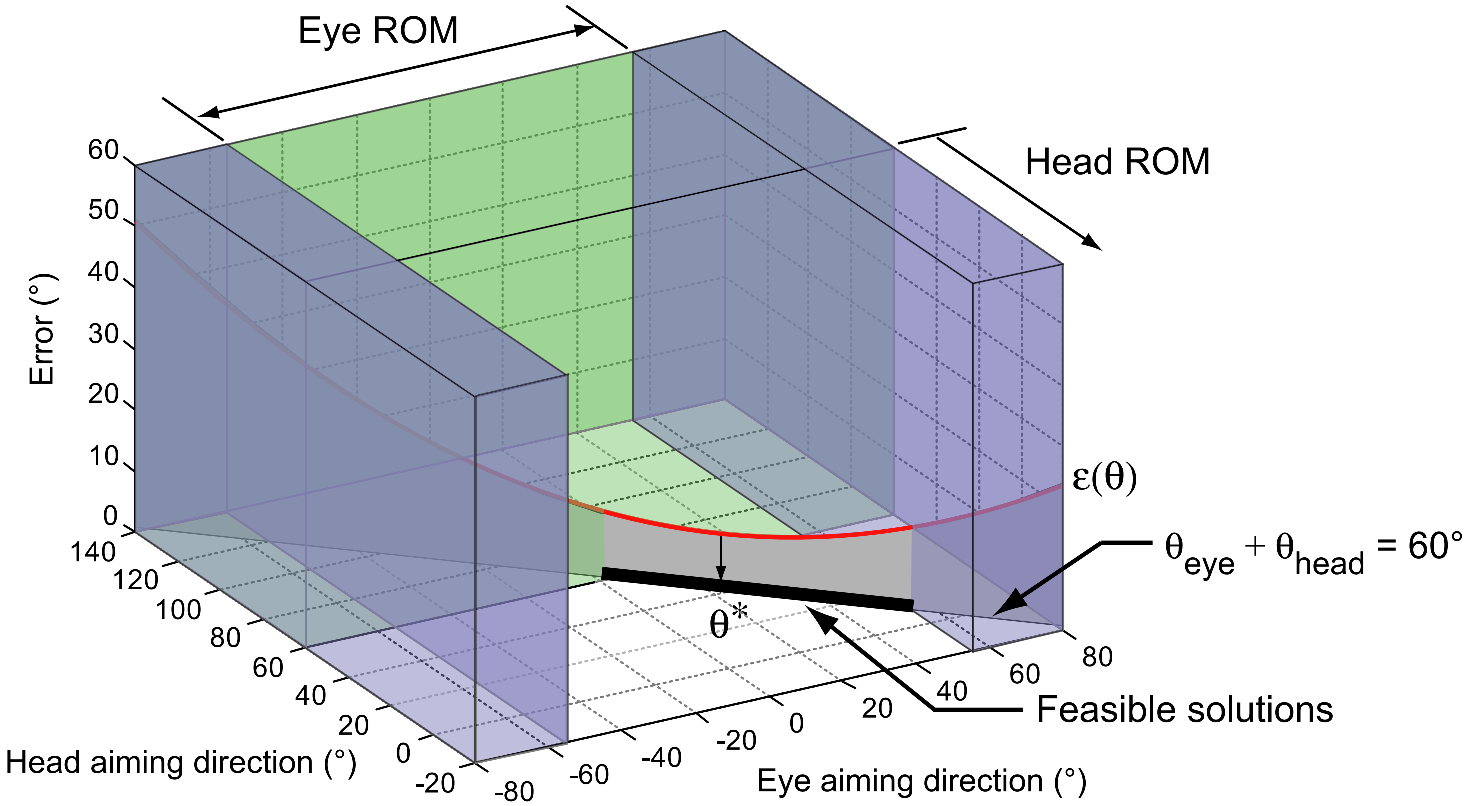
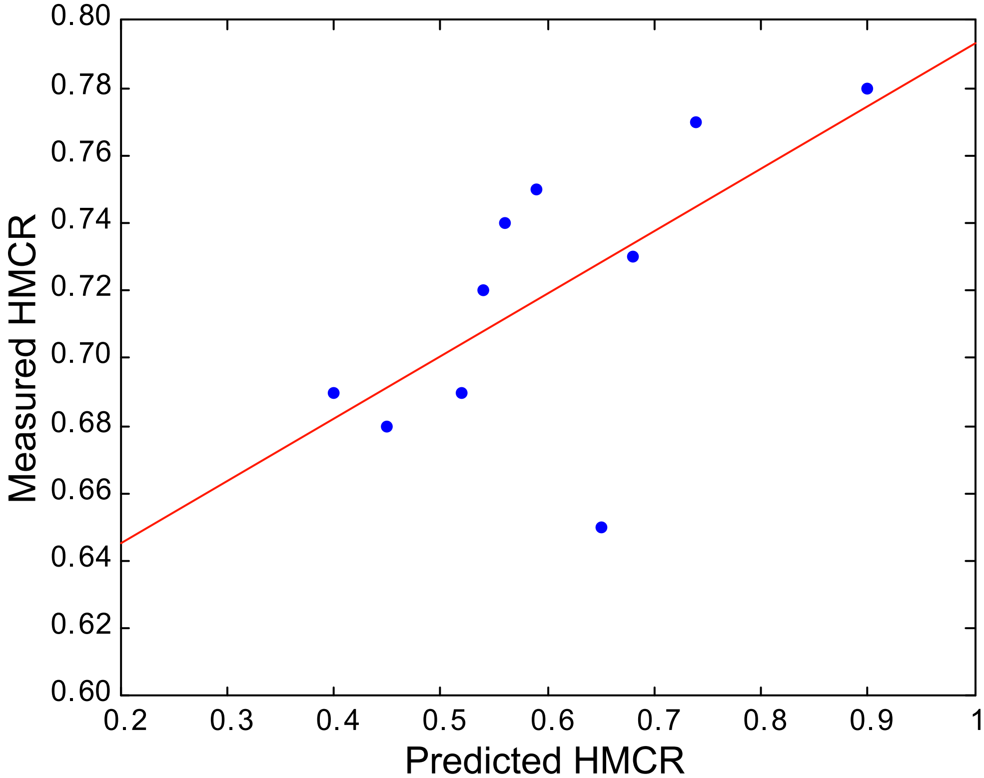

35
30
25
20
15
10
5
E rror (deg)
100
50
0
-50
-100
Head Orientation (deg)
-100
-50
0
50
100
Target Orientation (deg)

Figure 5



Eye ROM
Head ROM
60
50
40
30
20
10
0
Error (°)
ε(θ)
θeye + θhead = 60°
θ*
Feasible solutions
140
120
100
80
60
40
20
0
-20
Head aiming direction (°)
-80
-60
-40
-20
0
20
40
60
80
Eye aiming direction (°)

Figure 6



0.80
0.78
0.76
0.74
0.72
0.70
0.68
0.66
0.64
0.62
0.60
Measured HMCR
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Predicted HMCR

Table Titles

Table 1. Coefficients of the fitting models for initially intended head movement amplitudes

Table 2. Coefficients and significance of the aiming error models

Table 1

Subject	1	2	3	4	5	6	7	8	9	10	Mean (SD)
	Intended Amplitude vs. target eccentricity										
b_1	12.53	17.52	19.53	23.67	18.98	18.47	25.94	20.86	21.17	24.27	20.29 (3.86)
b_2	55.55	10.38	25.35	22.03	17.19	23.63	22.50	19.35	50.02	18.51	26.45 (14.54)
R^2	0.39	0.30	0.45	0.70	0.38	0.50	0.50	0.41	0.52	0.42	

Table 2

Subject	1	2	3	4	5	6	7	8	9	10
β	-3.6438	0.0743	0.9311	1.6861	5.8689	-0.1567	-0.6686	-1.1593	3.7410	2.3106
	0.0031	0.0012	0.0009	0.0020	0.0027	0.0009	0.0013	0.0023	0.0008	0.0014
	0.0029	0.0018	0.0006	0.0007	0.0014	0.0011	0.0010	0.0019	0.0004	0.0001
R^2	0.86	0.36	0.31	0.81	0.69	0.49	0.51	0.72	0.17	0.48
F	726.13	67.13	51.19	506.68	269.00	110.66	125.50	295.08	22.97	110.74
p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00