Coincidence Anticipation Timing Responses with Head Tracking and Eye Tracking

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BACKGROUND: Head tracking movements are common in interceptive tasks. The benefits of these movements are unclear. The purpose of this study was to compare coincidence anticipation timing (CAT) responses for a simulated approaching object when the eyes were used in tracking the object and when the head was used in tracking the object.

METHODS: A total of 29 subjects participated. A Bassin Anticipation Timer consisting of a track of sequentially illuminated lights was used to simulate an approaching object at velocities of $223\ cm \cdot s^{-1}$ to $894\ cm \cdot s^{-1}$. Each velocity was used 10 times under 2 conditions. In one condition, subjects were told to turn the eyes with the stimulus. In the other condition, subjects viewed the stimulus through apertures and were told to turn the head with the stimulus. Subjects pushed a button to coincide with illumination of the final light on the track.

RESULTS: Signed CAT errors, unsigned CAT errors, and variable CAT errors were compared between the head movement (HM) and eye movement (EM) conditions. No significant differences were noted for the signed errors (mean signed error at $894\ cm \cdot s^{-1}$; 10.3 ± 75.4 ms (HM), -16.1 ± 51.0 ms (EM). However, the unsigned and variable errors were significantly larger at some stimulus velocities in the head movement condition [mean unsigned error at $894\ cm \cdot s^{-1}$: $82.6.0 \pm 45.9$ ms (HM), 59.0 ± 22.4 ms (EM); mean variable error at $894\ cm \cdot s^{-1}$; 78.0 ± 37.8 ms (HM), 49.2 ± 17.1ms (EM)].

DISCUSSION: Head movement did not result in improved CAT performance compared to eye movements. Further work will be required to determine whether these results are generalizable to situations where head tracking is required but apertures are not worn.

KEYWORDS: coincidence anticipation timing, eye tracking, head tracking, helmet mounted cueing.

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Recently, it has been shown that athletes primarily move their heads in batting and catching approaching balls.[15,16,23] However, it is unclear whether this behavior imparts advantages in making the interdependent judgments of when and where an object will arrive.[4,20,36] Predictive tracking is also necessary in other endeavors such as driving and video game play.[21,32] To that end, elite military pilots are considered tactical athletes due to the physiological demands their environment places on them.[34] Further understanding of spatial-temporal judgment can be applied to aviators to enable higher performance in a dynamic environment.

A question for pilots is whether approaching targets should be followed with the head or with both the eyes and head. While head movement monitoring devices are currently employed in helmet mounted cueing systems on some military aircraft,[25,26,37] eye movement monitoring devices are currently under development to augment head movement monitors in these tasks, although there are many complexities that must be considered.[9,29,35]

At least part of the interest in eye movement monitoring devices is that control of eye movement and eye positioning is finer than head movement control, although tracking an object with head rotation does not appear to negatively influence gaze

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(eye rotation + head rotation) tracking when the head and eye are normally coordinated.[14] If head tracking does not lead to significantly greater losses of target fixation compared to eye-head tracking, and head tracking is better than or at least equal to eye-head tracking for predicting when and where an object will arrive, then perhaps the current generation of head movement monitoring technologies should continue to be employed for pilots.

Coincidence anticipation timing responses require an individual to time a response such as a button press or a hand motion to coincide with the time of arrival[5] of an approaching object (e.g., intercepting an adversarial target or collision avoidance).[8,11,13] The purpose of this study was to compare coincidence anticipation timing responses for a simulated approaching object when observers from the general population were required to move primarily the head in the direction of the object and when these observers primarily moved the eyes in the direction of the object.

METHODS

Subjects

This study and the associated consent forms were approved in advance by The Ohio State University Biomedical Sciences Institutional Review Board. Each subject provided written informed consent before participating. Data were collected from 29 subjects between the ages of 18 and 50. Subjects were recruited through an email to individuals at the Ohio State University College of Optometry, through a publicly available recruitment website provided by the Ohio State University Center for Clinical and Translational Science, and by word-of-mouth. Subjects were required to have visual acuity of 20/20 in each eye, 60 s of stereoacuity or better, and no strabismus (as assessed with a unilateral cover test) in primary, left, or right gaze.

Equipment and Materials

A survey evaluating the level of participation in organized sports was also conducted. After the entrance tests, an eye movement monitor consisting of cameras (ISCAN Inc., Woburn, MA, USA) mounted on a spectacle frame was placed on the subject as was a headband with a magnetometer-based head movement monitor (Parker LORD MicroStrain, Williston, VT, USA). These devices were used to ensure subjects mostly moved the head in the head tracking trials and mostly moved the eyes in the eye tracking trials. Only monocular recordings from the left eye were made with the eye movement monitor, and only horizontal recordings of both the eye and the head movements were made with the eye and head movement monitoring devices.

Coincidence anticipation timing was measured using a Bassin Anticipation Timer (Lafayette Instruments, Lafayette, IN, USA). A recent systematic review of coincidence anticipation timing studies from 2011 to 2017 showed the Bassin Anticipation Timer remains the most commonly used device to assess these responses.[8] While the stimulus motion is less complex than the trajectory of targets that a pilot may be required to follow, the Bassin Anticipation Timer allows for careful control of the stimulus speed and randomization of these speeds. In addition, the stimulus approaches in real depth, unlike the stimuli in computer simulations.

The Bassin Anticipation Timer (BAT) consisted of a linear track of lights 3.58 m in length. Each light is red, except for the yellow cue light at the end of the track opposite the subject. The LEDs are 10 mm in diameter and separated by about 4.5 cm. The lights illuminate sequentially to simulate movement along the track. The BAT was placed on a black tabletop 1.21 m off the floor and therefore below the subjects' eyes. A computer was used to select the stimulus speeds in 1-mph increments and to randomize the order in which these speeds are used. The coincidence-anticipation responses can be measured with a high degree of accuracy (samples in the current study were acquired every 0.5 ms for all but one subject for whom samples were acquired every 5 ms). A diagram of the experimental set-up is shown in **Fig. 1**. The subjects stood within a square (42 cm × 40 cm) at the end and to the left side of the track (that is, the subject's right eye was nearer to the BAT track). As assessed in a previous study from our laboratory,[13] subjects were about 56 cm from the BAT track. The square in which the subjects stood was centered on the final light at the end of the track. Therefore, for an observer positioned at the end of the BAT track in this manner, the horizontal angular difference between the cue light and the target light was about 81° and the vertical angular difference between these lights was about 35°.

Procedure

The subjects were tested in two randomized conditions. In one condition (head movement condition), subjects were fitted with aperture goggles over the eye movement monitor. The aperture goggles were constructed out of cardboard and fit snugly over the eye tracking apparatus. The apertures in these goggles consisted of two moveable slits that measured about 25.4 mm horizontally and about 5.5 mm vertically. The apertures could be slid horizontally, which allowed for adjustment to accommodate the subject's interpupillary distance. Since the goggle slits rested about 5.08 cm to 5.72 cm from the subjects' eyes, the horizontal monocular field of view created by the aperture was approximately ±13° and the vertical angular field of view was about ±2.9°. The slit design of the aperture goggles (as opposed, for example, to a pinhole design) was employed so that if eye movements associated with the rotational vestibulo-ocular reflex or vergence eye movements occurred, sight of the target was less likely to be lost. Finally, once the slits were adjusted to the subject's interpupillary distance, subjects were tested for binocularity by asking them to center the cue light in the right and left apertures. Vergence eye movements were not expected to result in a loss of fixation with the apertures in place. For example, for an observer with a height of 172.7 cm and an interpupillary distance of 6.4 cm, the vergence demand for the target light at the end of the track nearest the subject was

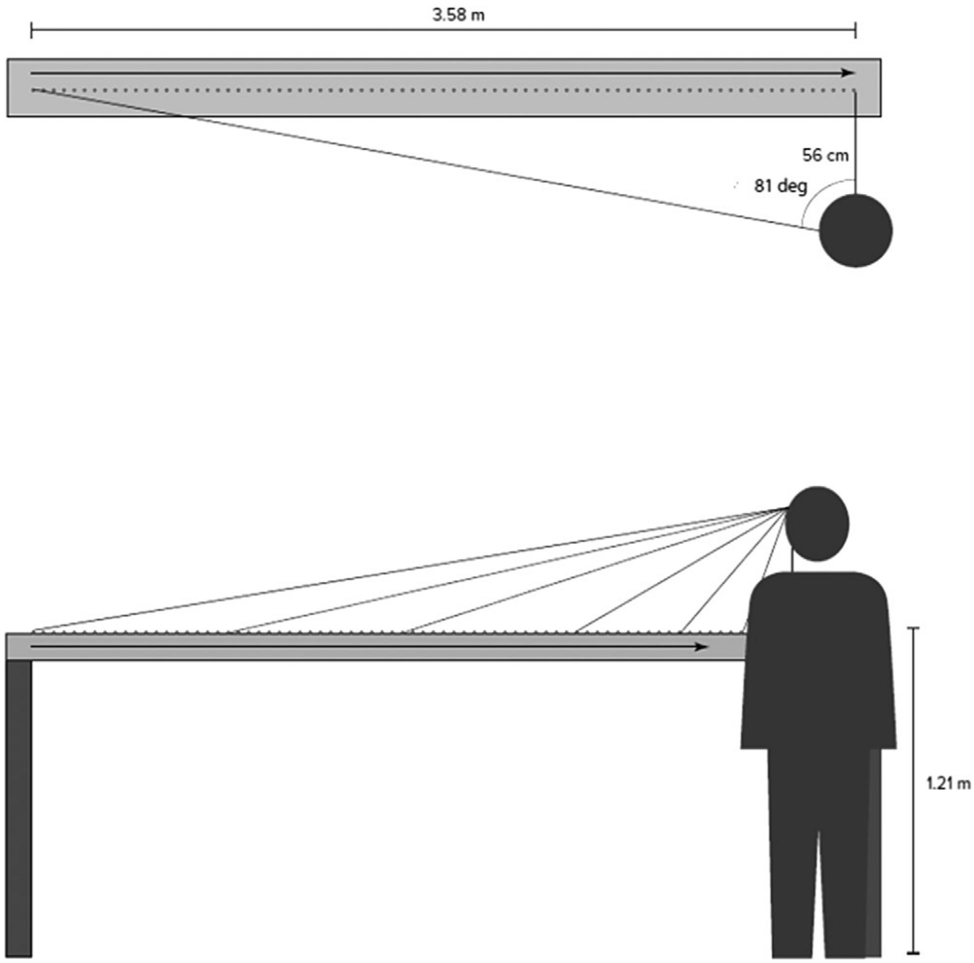

Fig. 1. Diagram of the experimental arrangement. The top drawing shows the view from above the subject and the bottom drawing shows the view from behind the subject. As the illuminated LED approaches, the angular location of the LED relative to the subject changes in both the horizontal (81°) and vertical (35°) directions.

about 4.80°. Subjects were then instructed to track the approaching lights with their head and to push the pushbutton at the same time the last light on the track was illuminated. In the other condition, no apertures were worn. Subjects were instructed to keep their head still and to track the light only with their eyes (eye movement condition). In this condition subjects were first instructed to orient their head so that they could see the cue light at the end of the track opposite the subject and the final light at the end of the track closest to the subject while moving only their eyes. Once their head was oriented appropriately, subjects were instructed to keep the head stationary and to press the pushbutton to coincide with illumination of the final light on the track.

The experiment was controlled by a computer program (PsymSoft, Lafayette Instruments, Lafayette, IN, USA). To reduce anticipation, the cue light at the end of the track opposite the subject remained lit for a random amount of time from 0.50 to 2 s prior to the lights approaching the subject. In each condition, four linear target velocities were each used randomly 10 times. These linear velocities were 223 $cm \cdot s^{-1}$ (5 mph), 447 $cm \cdot s^{-1}$ (10 mph), 670 $cm \cdot s^{-1}$ (15 mph), and 894 $cm \cdot s^{-1}$ (20 mph). Therefore, for each condition, 40 trials were usually presented.

Data were collected with an 11-bit analog-to-digital converter (USB-1208FS, Measurement Computing, Norton, MA, USA). The pushbutton responses were recorded in synchrony (2000 Hz for 28 subjects, and 200 Hz for 1 subject) with outputs from a photodiode placed over the cue (start) light and a second photodiode placed over the "target" light at the end of the track adjacent to the subject. By synchronizing these components, the total time for the lights to "travel" from one end of the track to the other and the time at which the subject depressed the push-button could be determined. It was then possible to compare the time between when the final light on the track was illuminated and when the subject pressed the push button. Once the final target was illuminated, the BAT was reset by the examiner (cue light reilluminated) using a push button specifically provided for that task.

The head movement monitor and eye movement monitor's analog data were also recorded in synchrony with the other analog inputs. For one subject, the output from the head movement monitor was not recorded.

A custom computer program was used to analyze the raw analog data. The program determined the start and finish of each trial (using output from the two photodiodes) and calculated the difference between the time at which the final light was illuminated and the time at which the subject pressed the pushbutton. The difference was displayed as a signed response error.

Statistical Analysis

Minitab 17.0 (Minitab, Inc., State College, PA, USA) statistical software was used to calculate means and standard deviations for signed (constant) errors for all subjects, unsigned (absolute) errors for all subjects, and variable error (mean of the standard deviations of the constant signed errors for the subjects). All of these values are commonly calculated in studies of coincidence anticipation timing.[3] The signed errors demonstrate response biases (i.e., early or late responses), while the unsigned errors reflect the overall accuracy of the responses.

The remaining analyses were completed using IBM SPSS Statistics Version 28 (IBM Corporation, Armonk, NY, USA). Studentized residuals were calculated in SPSS for each combination of factors (movement condition and stimulus velocity), and the normality of these residuals was assessed using the Shapiro-Wilk test for the signed, unsigned, and variable errors. Only for the signed errors were the majority (6/8) of the combinations normal. Therefore, for the signed errors a two-factor [movement condition (head movement or eye movement) and stimulus velocity] repeated measures analysis of variance was completed using IBM SPSS Statistics Version 28 (IBM Corporation, Armonk, NY, USA). Effect size measures were also calculated and are reported as partial eta-squared values. On the other hand, for the unsigned errors, only three of eight combinations of movement condition and stimulus velocity met the assumption of normality and only one of the eight combinations met this assumption for the variable errors. Therefore, at each stimulus velocity, comparisons between the unsigned errors and comparisons between the variable errors for the eye movement and head movement conditions were performed using the Wilcoxon matched pairs nonparametric test in SPSS.

While the primary purpose of the horizontal eye and head movement recordings from the monitoring devices was to verify that subjects followed the instructions in each of the movement conditions and not necessarily to compare gaze errors in the two conditions, an analysis of a subset of these recordings was performed to assess variability in the gaze tracking strategy between the conditions. At each stimulus velocity for each subject, the last trial in which that velocity was used was found and those horizontal eye and head movement data associated with that trial were plotted and visually inspected. If that trial could not be analyzed due to noise in the recordings or due to blinks, then the next to last trial using that stimulus velocity was examined. This procedure was continued until analyzable data were identified. The beginning of those data from the selected trial were set to zero, and then these eye and head movement data were converted to degrees of rotation by dividing them by their respective calibration gains. The gain of the eye movement monitoring device was determined by rotating an artificial eye through known angles of rotation and then recording the output from the eye movement monitor at each angle.[12] The gain of the head movement monitoring device was determined by rapidly rotating the head movement monitor through known angles and recording the output from this monitoring device. Prior to the calibration, head rotation data were smoothed using a 41-point averaging filter. The change in the horizontal gaze angle was determined by summing the calibrated eye and head rotations. No filtering was applied to the eye rotation data and there was no adjustment for small latencies (<50 ms) measured previously for the head and eye tracking devices.[17]

RESULTS

Of the subjects, two had never participated in organized sports. Of the 27 individuals, 19 who had participated in organized sports played a sport where an approaching object must be intercepted (e.g., baseball). The other eight individuals had participated in sports where object interception was less likely to be required (e.g., dance).

Overall, there were 12 instances in which data from a trial could not be included in the analyses. In most of these cases, data were missing because subjects did not press the button. In one trial of one subject, the computer program failed to properly detect the onset of the stimulus and in one trial from another subject a response was eliminated because it was extremely (2.1 s) late. Finally, there were four cases where an extra data point was recorded.

The head and eye movement traces for each trial were plotted and visually inspected as described in the methods. There were individuals for whom excessive blinks or excessive noise in the recordings precluded analysis at particular stimulus velocities in a particular condition. In addition, those data recorded at 200 Hz for one subject were not included. Overall, for each combination of movement condition (head or eye) and stimulus velocity, those data from 19 to 21 subjects were included in the final analyses. In order to determine whether subjects followed the directions provided for each movement condition, the mean horizontal values for each condition at each velocity were plotted as shown in **Figs. 2A–H**. These mean data suggest the subjects largely adhered to the instructions. Several findings of interest can be seen in these plots.

First, at the lowest stimulus velocity there is a significant horizontal gaze tracking lead in both the head and eye movement conditions. This gaze tracking lead declines as the stimulus velocity increases. In addition, in the head movement condition there is a late eye movement in the direction of the stimulus. This is reminiscent of the head and eye movement results from a study on gaze tracking in cricket batters, where it was shown that the head was maintained close to the ball while the eye was placed at or near the expected location of the ball when the ball arrives at the batter.[23]

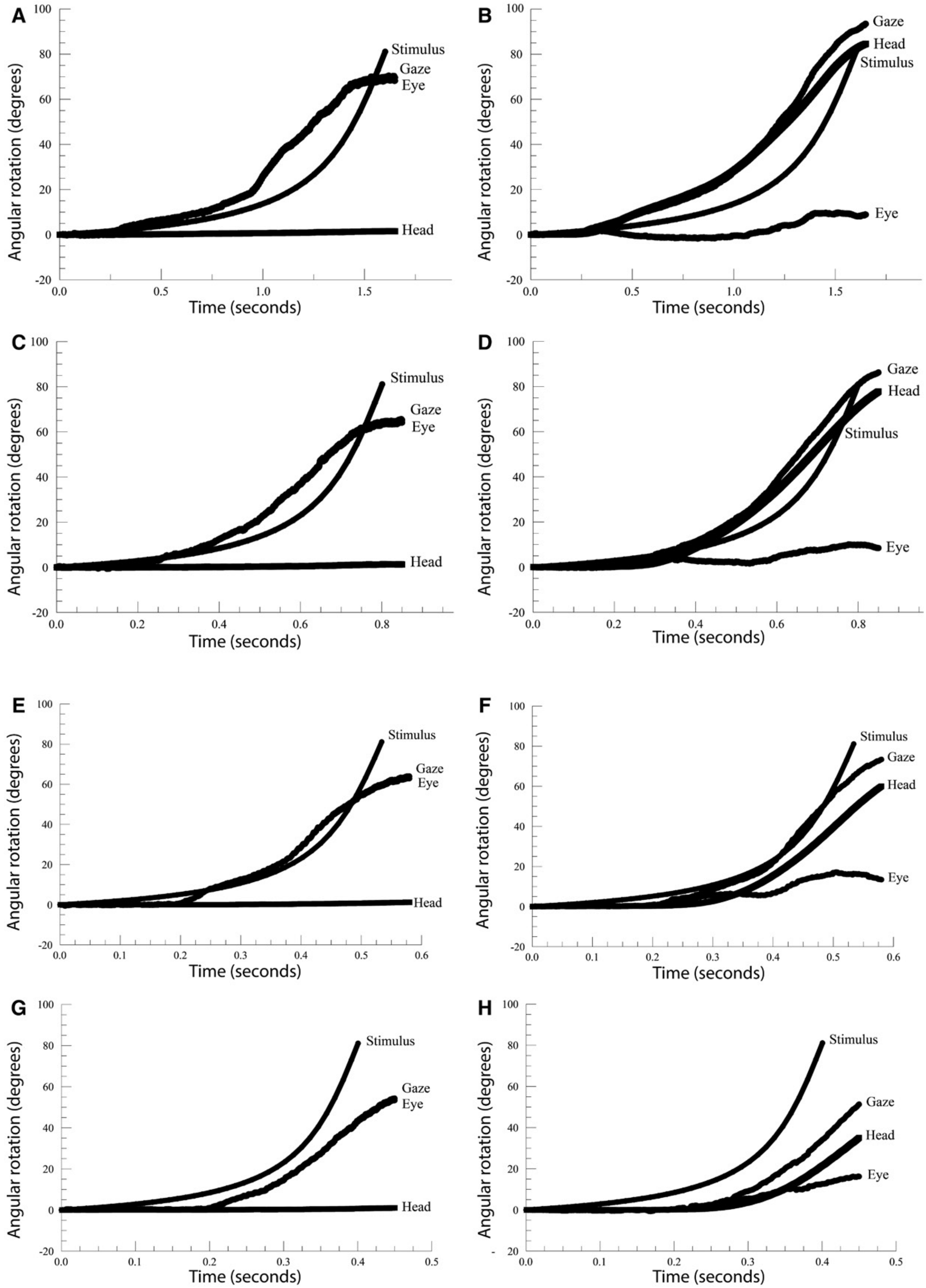

Fig. 2. Mean horizontal head and eye movement responses. A) Eye movement condition, 223 cm · s^{-1}. B) Head movement condition, 223 cm · s^{-1}. C) Eye movement condition, 447 cm · s^{-1}. D) Head movement condition, 447 cm · s^{-1}. E) Eye movement condition, 670 cm · s^{-1}. F) Head movement condition, 670 cm · s^{-1}. G) Eye movement condition, 894 cm · s^{-1}. H) Head movement condition, 894 cm · s^{-1}.

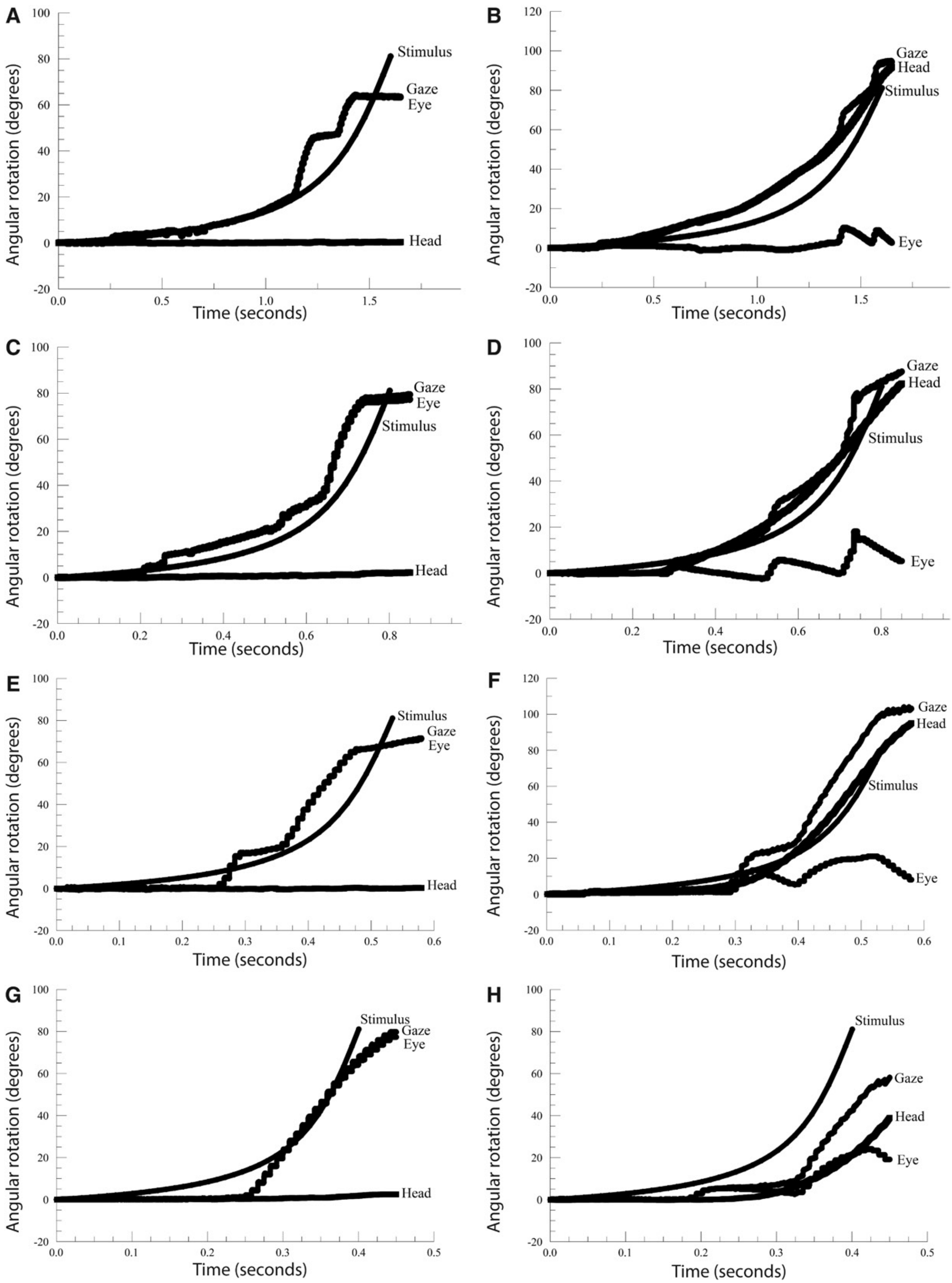

Fig. 3. Representative horizontal head and eye movement responses from individual subjects. A) Eye movement condition, 223 cm · s^{-1}. B) Head movement condition, 223 cm · s^{-1}. C) Eye movement condition, 447 cm · s^{-1}. D) Head movement condition, 447 cm · s^{-1}. E) Eye movement condition, 670 cm · s^{-1}. F) Head movement condition, 670 cm · s^{-1}. G) Eye movement condition, 894 cm · s^{-1}. H) Head movement condition, 894 cm · s^{-1}.

While there was variability in the horizontal head and eye movement behaviors between subjects, some representative examples from individual subjects for each combination of movement condition and stimulus velocity are shown in **Figs. 3A–H**. Inspection of these plots from the eye movement condition revealed that at lower velocities (223 cm · s^{-1} and 447 cm · s^{-1}), subjects often exhibited saccadic eye movements with angular velocities exceeding that of the stimulus.

As a result, the gaze was often near the end of the Bassin track prior to arrival of the stimulus. At higher stimulus velocities (670 cm · s^{-1} and 894 cm · s^{-1}), high velocity eye movements occurred with smaller or no periods of ocular pursuit. Compared to the lower velocity stimuli, it was more difficult to determine from visual inspection whether the high velocity eye movements that occurred in the high velocity stimuli trials were in fact saccades. Therefore, at a stimulus velocity of 894 cm · s^{-1}, the amplitude and duration of 17 apparent saccades were assessed. The relationship between the saccadic amplitude and duration is expected to follow the equation: saccadic duration (in ms) = 2.2*saccadic amplitude in degrees + 21.[7] The majority of the examined eye movements (15/17) largely followed the expected relationship between saccadic amplitude and duration, demonstrating that visual inspection was a reliable way to determine the presence of saccades even at the highest stimulus velocity. Compared to the lower stimulus velocities, gaze was more likely to be directed at the end of the stimulus trajectory at the same time or possibly after the stimulus arrived at the higher stimulus velocities.

Visual inspection of the plots of horizontal movement from the head movement condition revealed the following. At the lowest stimulus velocity (223 cm · s^{-1}), a head tracking lead with variable small eye movements occurred. In some cases, an eye movement opposite to the head movement was seen earlier in the trial, but at some time in the stimulus path many subjects demonstrated at least one cycle consisting of a high velocity eye movement in the direction of the head followed by a slower movement opposite to the head movement.

At stimulus velocities of 447 cm · s^{-1} and 670 cm · s^{-1}, the head movement was closer to that of the angular movement of the target and, in some cases, there were fast and slow alternating oscillations and an ocular saccade close to the time of target arrival. The eye movement at a stimulus velocity of 670 cm · s^{-1} was often just a singular high velocity movement near the end of the trajectory. At the highest stimulus velocity (894 cm · s^{-1}), a pattern of head and eye movement similar to that seen at a stimulus velocity of 670 cm · s^{-1} was found. However, the head and eye movements were shifted to later times at the highest stimulus velocity, resulting in a lag for gaze position.

The mean signed error and the sample standard deviation of this mean for the subjects in each condition are shown in **Fig. 4A**. The mean unsigned error and the sample standard deviation of this mean for the subjects in each condition is shown in **Fig. 4B**. Finally, the mean and sample standard deviation of the variable errors for each condition are shown in **Fig. 4C**.

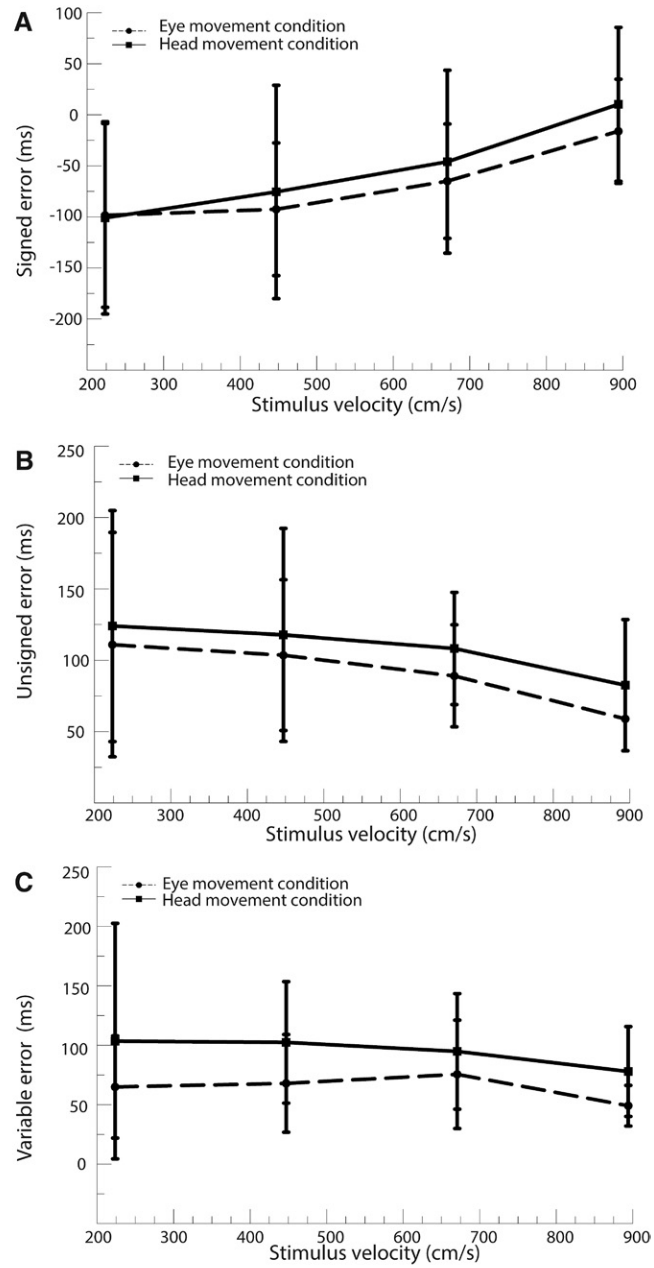

Fig. 4. Mean and standard deviation of coincidence anticipation timing errors. A) Signed errors. B) Unsigned errors. C) Variable errors.

For the signed errors, the results of the repeated measures ANOVA were as follows. The Greenhouse-Geisser correction was applied to correct for violation of sphericity (Mauchly's sphericity test). Movement condition (head movement vs. eye movement) was not significant [F = 2.87(1,28), P = 0.101, η_p^2 = 0.093], while velocity was significant [F = 40.02(1.86,52.05), P < 0.001, η_p^2 = 0.588]. The interaction between movement condition and velocity was not significant [F = 1.82(2.69,75.20), P = 0.156, η_p^2 = 0.061]. Since movement condition was not significant, no further analyses were performed.

Significant differences in the unsigned errors (Wilcoxon, P < 0.05) between the head and eye movement conditions occurred at stimulus velocities of 670 cm · s^{-1} (P = 0.008) and

894 cm · s^{-1} ($P = 0.012$). Significant differences in the variable errors for the two movement conditions occurred at stimulus velocities of 223 cm · s^{-1} ($P = 0.005$), 447 cm · s^{-1} ($P = 0.004$), and 894 cm · s^{-1} ($P = 0.002$).

DISCUSSION

The signed errors were not significantly different for the head and eye movement conditions, while the unsigned errors were significantly larger at the two highest stimulus velocities for the head movement condition. The variable errors were significantly larger in the head movement condition at three of the four stimulus velocities.

There are some potential explanations for the larger unsigned and variable errors at some stimulus velocities in the head movement condition. Some investigators have demonstrated that pursuit tracking of approaching objects improves coincidence anticipation timing compared to steady fixation.[2,24,31] An extraretinal neural signal associated with ocular pursuit (and potentially with head movement) may provide predictive information on the approaching object's time to contact,[2] and ocular pursuit may shift the observer's attention in the direction of the "interception" point.[22] More accurate gaze tracking in the eye movement condition compared to the head movement condition may improve time to contact judgments by enhancing one or more of these aforementioned variables.[18] Additional gaze tracking data, in which individual calibrations of the eye movement monitor are used and two-dimensional eye movement recordings are included, will be needed to fully examine whether gaze tracking errors in the eye movement condition are smaller than those in the head movement condition and whether these errors correlate with coincidence anticipation timing performance.[12] It might be argued that the influence of the gaze tracking errors on the differences in the unsigned and variable errors in the eye movement and head movement conditions is diminished because the gaze tracking strategy in both conditions was to shift the gaze to a location at or near the end of the Bassin track prior to or at the time of arrival of the stimulus. However, given the results of a previous study using the Bassin Anticipation Timer suggested the reaction time (including the premotor, motor, and button-press times) was between 200 ms and 300 ms,[13] it is possible the late gaze shifts in the current experiment may have occurred after at least a portion of this reaction time period had elapsed. Therefore, these gaze movements may not have directly influenced the results of individual trials. On the other hand, the timing and accuracy of these late gaze shifts may have improved subsequent coincidence anticipation timing responses by placing gaze at or near the location at which the stimulus arrived.[1]

Another aspect of eye tracking that may influence coincidence anticipation timing responses is the occurrence of catch-up saccades. It has been shown that visuomotor movements to intercept smoothly moving targets occur earlier when the target is tracked with a combination of pursuit eye movements and forward (in the direction of the object) catch-up saccades compared to situations where tracking consists of pursuit and backward saccades.[19] While saccades were very common in the current experiment, as mentioned above, these saccades often appeared to be anticipatory and therefore gaze was directed ahead of rather than at the target. In future studies, it will be interesting to compare the influence of anticipatory saccades on coincidence anticipation timing performance to that of catch-up saccades that occur during continuous pursuit of an object.

There are other factors that may have resulted in worse coincidence anticipation timing performance in the head movement condition. The reduced field of view with the aperture potentially disrupted the normal coordination of the eye and the head, resulting in an increase in cognitive workload. For example, in the head movement condition subjects were required to cancel the rotational vestibulo-ocular reflex.[33] As evidence that viewing with a reduced field of view can disrupt perceptual motor coordination, Sandor and Leger demonstrated that wearing apertures over the eyes reduced the ability of observers to maintain a ring around a moving object using a joystick.[28] Further, Bongers and Michaels[4] concluded that restricting head movements (with a neck brace) reduces the time required by subjects to judge where a launched ball will land. On the other hand, in the eye movement condition, reducing head movement may have negatively influenced coincidence anticipation timing performance compared to situations where more natural eye and head coordination is employed. This is because head movement has been hypothesized to occur in interceptive tasks to maintain an approaching object in a constant egocentric direction and this is potentially advantageous for visuomotor coordination.[23]

Other potential influences of the aperture on the coincidence anticipation timing errors in the head tracking condition must be considered. For example, in the eye movement condition the final target LED could be viewed peripherally throughout the entire trial whereas this LED was initially obscured in the head movement condition. Such a difference might result in improved coincidence anticipation timing responses in the eye movement condition.[2,6] However, one would expect that if the aperture influenced the timing responses in this way, then this effect would decline at lower stimulus velocities. This is because at lower velocities more time would have been available to view the target LED peripherally. Differences in the unsigned errors between the head and eye movement condition were significant only at the two higher stimulus velocities, but differences in the variable errors were significant at three of the four stimulus velocities. Thus, the effect of obscuration of the final location of the stimulus by the aperture is unclear.

Finally, one other potential influence of the aperture should be mentioned. It is known that perception of the motion of an object that is being pursued with the eyes can be affected by the presence of a structured background.[6,27,30] In addition, Tresilian[31] demonstrated that coincidence anticipation timing responses were improved when the path of an approaching object was illuminated compared to dark viewing conditions.

Perhaps the aperture negatively influenced coincidence anticipation timing responses by reducing the angular extent of the background that could be viewed.

In summary, signed coincidence anticipation timing errors were similar between the eye movement and head movement conditions. However, unsigned errors and variable errors were larger at some stimulus velocities in the head movement condition.

Helmet mounted displays used by pilots that aid in object targeting can take many forms such as visor projected,[9] night vision goggle projected,[10] or monocular reticle.[26] These devices use head, eye, and head-eye movements to provide information to the pilot. Technological advances using head and eye tracking will continue to push human machine interaction which will require better understanding of how head and eye movements work together in spatial-temporal judgment. This study demonstrates that in using an aperture to require head movements in tracking an approaching object, coincidence anticipation timing performance is reduced compared to tracking the target with eye movements in the absence of an aperture. Further studies will be required to determine whether the aperture leads to disordered coordination of the head and eye and whether this disruption, along with a reduction in the field of view, negatively influences coincidence anticipation timing.

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