Article • Horizontal Head and Eye Rotations of Non-Expert Baseball Batters

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ABSTRACT

Purpose: The purpose of this experiment was to measure the horizontal head rotations, eye rotations, and gaze tracking responses of non-expert baseball players in tracking a pitched ball and to compare these data to those from intercollegiate baseball players.

Methods: A pneumatic pitching machine propelled tennis balls toward participants at about 77mph. Participants called out numbers and the color of these numbers written on the balls. Head movements were recorded with an inertial sensor attached to a batting helmet, and eye movements were recorded with a wearable infrared video tracker.

Results: Data were analyzed for 14 non-expert participants, and these data were compared to those from a group of 15 intercollegiate players. For both the non-expert and intercollegiate groups, head movements in the direction of the ball were larger than eye movements at all six elapsed times of interest. At the end of the pitch trajectory, head movements were significantly larger and gaze errors were significantly smaller for the non-experts. There were no significant differences in the variability between the non-experts and intercollegiate participants. When the non-experts were divided by experience, the group with no baseball experience exhibited eye movements opposite to the head movement and larger head movements than the other groups.

Conclusions: In tracking a pitched ball, non-expert baseball batters adopted a similar pattern of head-eye coordination to that of intercollegiate baseball batters. Non-experts with no baseball experience demonstrated larger eye movements opposite to the ball, suggesting that cancellation of the rotational vestibulo-ocular reflex may be less efficient in this group.

Keywords: baseball, batting, eye rotations, gaze tracking, head rotations, sports vision

Introduction

The visual attributes of more- and less-accomplished baseball players have been compared previously. Differences in these characteristics may contribute to variances in on-field performance between these two groups.[1-4]

For example, Laby et al.[1] measured visual acuity, distance stereoacuity, and contrast sensitivity of a group of professional (major and minor league) baseball players and concluded that the major league players performed significantly better with distance stereoacuity and contrast sensitivity compared to both the general population and to the minor league baseball players. Hoffman et al.[2] found better contrast sensitivity in a group of college baseball players compared to a group of non-athlete graduate students, and Rouse et al.[3] reported better dynamic visual acuity in a group of college baseball players compared to non-athlete graduate students. Still other studies (not necessarily specific to baseball) can be found that suggest that some binocular and other oculomotor functions may be better in athletes compared to non-athletes or better in successful athletes compared to less successful athletes,[4-10] although a recent paper suggests that a significant proportion of athletes may demonstrate oculomotor deficits.[11]

Head rotation, eye rotation, and gaze tracking behaviors of more- and less-experienced players during baseball batting have only been compared in one previous study.[4] Such comparisons may be important, as the appropriate tracking strategy may impart advantages for batting. Bahill and LaRitz[4] compared the head and eye movements of graduate students, collegiate players, and a Major League Baseball (MLB) player as participants tracked (but did not bat) a ball pulled toward them on a string at linear velocities between 60 and 100mph. These investigators reported differences between the MLB player and the other participants in terms of accuracy (the MLB player efficiently tracked the ball to closer distances), head and eye movements, and gaze (head plus eye) tracking strategy. Regarding head and eye movements, the MLB player used relatively equal-sized head and eye movements in tracking pitches, while some of the non-MLB players used unequal head and eye movements. In terms of overall tracking strategy, the MLB player tracked the ball continuously, while one of the other participants made a saccadic eye movement to a location ahead of the ball. The authors hypothesized that anticipatory saccades such as the one made by their participant might help batters to catch a glimpse of the ball as it crosses the plate, thereby providing information about the likely location of future pitches, while continuous tracking would be more useful when actually batting the ball.[4,12]

Thus, the differences between the MLB player and the other participants in head and eye movements and tracking strategy (and the associated variability amongst the non-MLB participants) were perhaps at least partially the result of differences between the MLB player and the other participants in interpreting what the task was (e.g., act as if you are hitting versus act as if you are "taking" a pitch) and not entirely the result of the less-experienced participants simply not employing the same (presumably "correct") behaviors as those of the MLB player. Indeed, a recently published study from our laboratory demonstrated that gaze tracking strategies varied when individuals were asked to "take" pitches compared to when these individuals swung a bat at pitches,[13] and Hubbard and Seng[14] also reported that head movement behaviors could vary depending on whether batters were "taking" or swinging at pitches.

In addition, although the work of Bahill and LaRitz[4] suggests that there may be differences in tracking strategy and tracking accuracy between baseball players with different levels of experience, their conclusions were derived from a total of just six complete pitches and fifteen partial pitches. As such, the influence of experience level on head movements, eye movements, and gaze tracking in baseball batters has not yet been fully addressed. The purpose of this experiment is to compare horizontal head and eye rotations and gaze tracking strategies of baseball batters at different levels of experience when all participants are provided with the same task instructions. In this case, the task is to call out numbers and the color of these numbers written on pitched balls. In comparing the eye, head, and gaze movements between two previous studies from our laboratory (one in which subjects did not bat but were required to call out numbers and the color of these numbers on pitched balls[15] and the other in which subjects batted the balls[13]), it was found

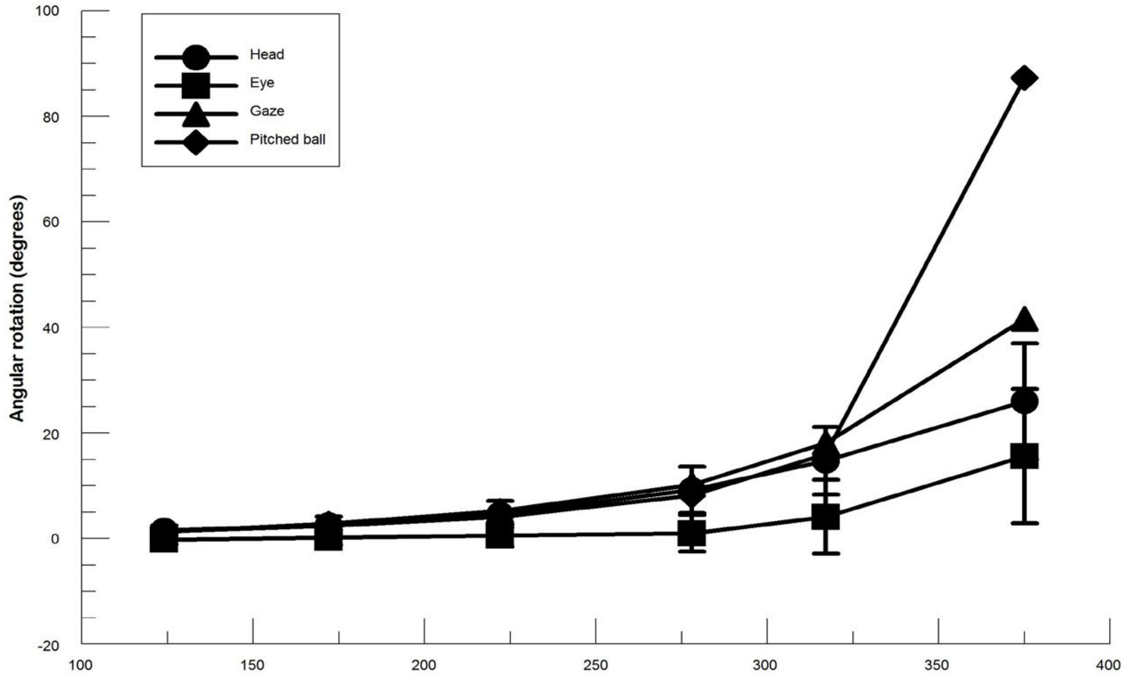

Figure 1. Overall head-, eye-, and gaze-tracking data (error bars are ±1 standard deviation) for the non-experts

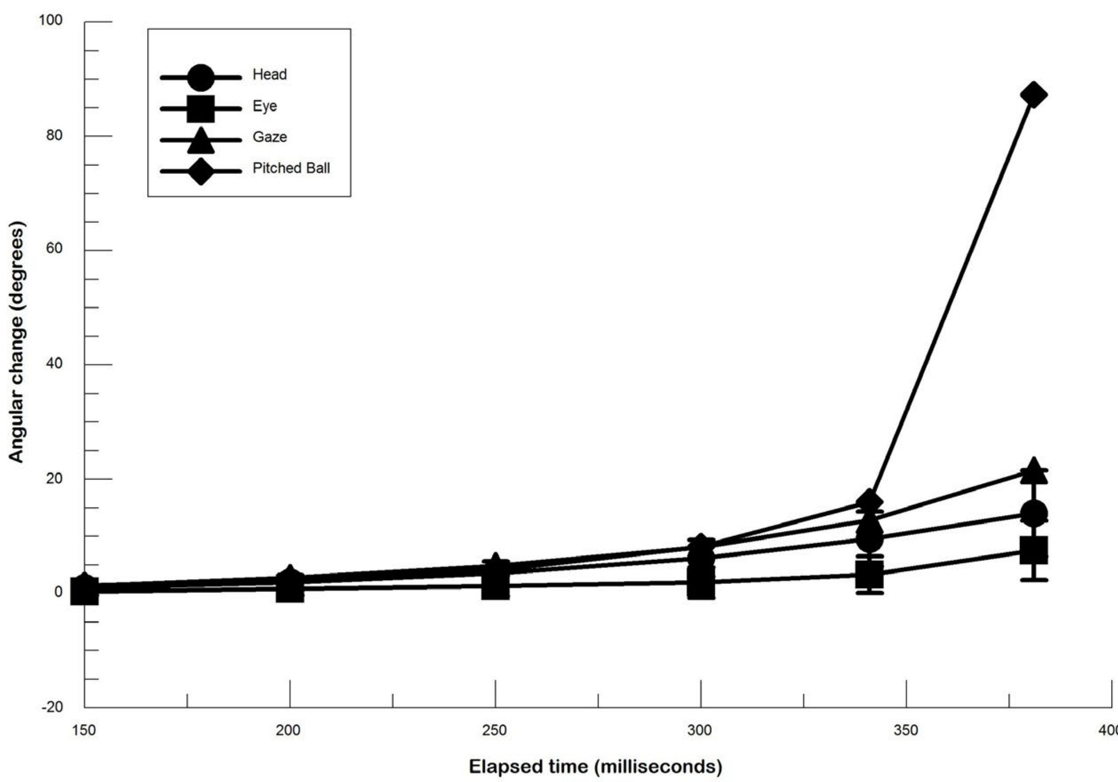

Figure 2. Overall head-, eye-, and gaze-tracking data (error bars are ±1 standard deviation) for the intercollegiate participants

that these movements were similar in the two cases throughout much of the pitch trajectory.

Methods

This study was approved by The Ohio State University Biomedical Sciences Institutional Review Board. All participants signed a written informed consent form prior to participation. Data were collected from 20 non-expert male baseball players. In this study, a non-expert player was defined as one who had never played intercollegiate or professional baseball. All participants were under 30 years of age. Monocular visual acuity was tested with a Bailey-Lovie chart. Mean logMAR visual acuity for the 14 participants whose data could be analyzed was 0.08 ± 0.1 for the right eye (Snellen equivalent = 20/24) and 0.06 ± 0.13 (Snellen equivalent = 20/23) for the left eye. The worst recorded visual acuity for a single participant was 0.32 (left eye) (Snellen equivalent = 20/42), with a right eye acuity of 0.20 (Snellen equivalent = 20/32). The dominant eye was not determined. The influence of ocular dominance on baseball batting is a controversial matter.[16]

Equipment

Much of the methodology used in this experiment has been described previously.[13,15]

Pitching Machine

Tennis balls were projected from a pneumatic pitching machine (Flamethrower®, Accelerated Baseball Technologies; Crystal Lake, IL). A light emitting diode (LED) flashlight and photodiode were vertically aligned across from one another and mounted at the end of the tube closest to the participant. This arrangement was used to assess the time at which the ball left the pitching machine tube, as the voltage from the photodiode changed when the ball passed over it.

The time required for the balls to traverse particular distances along the ball's trajectory was determined using a ballistic screen (Oehler Research, Model 57 Ballistic Screen; Austin, TX). The longest distance utilized was 42 feet 8 inches, which was the location of the participant relative to the pitching machine release point. This distance was the result of size constraints in our laboratory and is shorter than that used in professional baseball (60 feet 6 inches). A linear regression was used to fit the distance-versus-time data. This equation was then used to calculate not only the linear distance traveled by the ball at various elapsed times but also the horizontal angular change in ball location relative to the participant at these times. In order to calculate the angular change in ball location (Figures 1 and 2), it was necessary to employ the lateral distance from the ball's path to the batter's forehead (28 inches). The average linear velocity of the ball was calculated to be about 77 miles per hour.

Eye rotations

All participants were right-handed and stood in the right-handed batter's box. Horizontal eye rotations (in the orbit) were recorded using a video eye-tracker from ISCAN Incorporated (Burlington, MA). The ISCAN cameras were affixed to a spectacle frame, which was secured with a spectacle strap.

Previously, measurements from an ISCAN eye-tracker were found on average to be within 1 degree of those from a scleral search coil.[15] The noise in the eye-tracker was assessed as described in Appendix A. The standard deviation of eye-tracker values at angles of rotation from 35 degrees right to 35 degrees left was in all cases less than 10 arc minutes.

During the experiment, the analog output of the ISCAN system was recorded using an 11-bit analog-to-digital converter (USB-1208FS; Measurement Computing, Norton, MA). The horizontal amplification or gain of the ISCAN for each participant was determined using a five-point calibration. The total angular change required to fixate the most extreme calibration targets was 49.7˚. The fixation targets included the end of the PVC pitching machine tube and four fixation targets affixed to an adjacent wall that spanned much of the pitch trajectory. The participant was instructed to look at each of the five calibration points while maintaining a fixed head position, and the ISCAN output was recorded at each location. These data were then plotted against the required change in visual angle between each calibration point. The calibration gain for each participant was the slope of the regression line fit to these data ($r > 0.992$ in all cases).

Head Rotations

An inertial head-tracking device (MicroStrain 3DM-GX1) (LORD Corporation, Williston, VT) was tightly fastened to the top of a baseball batting helmet in order to measure horizontal head rotations.[13,15] The output of this device was also recorded in analog form using the same analog-to-digital converter as that used to record the eye-tracker signals. The gain of the MicroStrain remains constant between participants, so the calibration factor for the MicroStrain was determined by mounting the MicroStrain on a protractor and rotating it rapidly through various horizontal angles. Previously, measurements from this tracker were found on average to be within 1 degree of those obtained from a search coil.[15]

Data Recordings

The analog outputs from the ISCAN and MicroStrain devices were recorded in synchrony with the output from the photodiode (all at 2000Hz) using the analog-to-digital converter.[13,15]

Experimental Procedure

After the informed consent process and the visual acuity measurement, each participant was asked about their prior organized baseball experience. Then participants put on the ISCAN eye tracker and the batting helmet. The batting helmet was secured using a chin strap. The participants were asked to hold a baseball bat to emulate a batting stance, but participants were not permitted to swing the bat.

Next, the five-point ISCAN calibration was performed. Each participant was then shown two tennis balls. One tennis ball had a small (18mm x 8mm) number (0-8) written in six locations in black, and the other had numbers written in the same manner but in red. To minimize the influence of participants' interpretation of the task on head and eye movements and gaze tracking behaviors, participants were asked to call out the color and the number on the balls as they were pitched. Subjects' performance in naming the numbers and colors was not recorded, as it was found previously that performance on these tasks does not rise above chance levels.[15]

Fifty-two pitches were presented to each participant in two back-to-back trials. The time between pitches was typically about three to five seconds.

Results

Data could be analyzed for 14 of the 20 participants. Data from six participants could not be analyzed due to improper recording from at least one of the devices. For each of the 14 participants from which useable data were obtained, a single run (52 pitches) was analyzed. The second set of pitches was generally used for the analysis in most cases in order to reduce any variability resulting from acclimating to the pitch trajectory. For two participants, the first set of pitches was used due to recording artifacts in the second set of pitches.

Data from the head and eye trackers were analyzed using a computer program. The program applied a 41-point averaging filter to the eye and head tracking data, compensated for temporal delays (<50ms) in the recording devices, and calibrated these data by applying the gains of the respective devices. Finally, the program divided these head and eye tracking data into individual files (two seconds in duration) for each pitch.

The beginning of the useable data files was zeroed under the assumption that participants were looking at or near the opening of the PVC pitching machine tube at the start of each pitch.[15] The angular changes in horizontal head and eye positions from the beginning of the pitch to six elapsed times after the pitch was released were calculated. These elapsed times (124ms, 172ms, 222ms, 278ms, 317ms, and 375ms) were chosen such that the required angular rotations (1.4˚, 2.4˚, 4.1˚, 8.2˚, 16˚, and about 87˚, respectively) at these times matched those for which data were analyzed in a previous study from our laboratory.[15]

Prior to completing these data analyses, those data from the ISCAN for every individual pitch were graphed and then visually inspected for blinks. In cases where a blink occurred prior to an elapsed time of 375ms, the pitch was discarded. On the other hand, there was a large number of instances in which blinks affected only the last elapsed time of interest (375ms). In these latter cases, only those data obtained at 375ms were discarded.

The horizontal gaze angle was calculated by adding the angular changes in horizontal head and eye rotation from the beginning of the pitch to each of the elapsed times of interest. The signed gaze error was calculated by taking the difference between the required angular change in ball position and the angular change in gaze position (from the beginning of the pitch to the elapsed time of interest).

Participant Characteristics

Of the 14 participants, three (3) did not have any organized baseball experience, while the terminal level for the remaining 11 participants was Little League (n=5), high school junior varsity (n=2), and high school varsity (n=4).

Combined Head Movement, Eye Movement, and Gaze Data

The mean horizontal head rotation, mean horizontal eye rotation (in the orbit), and mean horizontal gaze positions at the six elapsed times of interest for all of the non-expert participants are plotted in Figure 1.

On average, the head was moved in the direction of the ball at a similar angular velocity to the ball for much of the pitch trajectory. The eye showed a small leftward (opposite to the direction of the head and the ball) movement early in the pitch trajectory, followed by a larger rightward movement in the direction of the ball late in the trajectory. Overall, mean gaze was directed near the ball throughout much of the pitch.

Non-Expert versus Intercollegiate Data

Permission was obtained from The Ohio State University Biomedical Sciences Institutional Review Board to compare head, eye, and gaze data from our non-expert participants with data recorded (and re-analyzed for the current study) in a previous study.[15] In this previous study, horizontal head and eye rotations were recorded from 15 Division 1 intercollegiate baseball players who were required to call out the color and number on tennis balls "thrown" by the same pneumatic pitching machine used in the current experiment. The experimental set-up in this previous study was very similar to that employed in the current study. Data from the previous study were analyzed in the same manner as that employed in the current study. For one subject, at one elapsed time of interest, the gaze error was calculated 2ms later compared to the other subjects.

As mentioned previously, the required gaze angles (1.4˚, 2.4˚, 4.1˚, 8.2˚, 16˚, 87˚) were matched as much as possible for comparisons between the non-expert and intercollegiate participants. The final angle (approximately 87˚) was associated with the time at which the ball reached the batter, so it varied slightly (<1˚) between the non-expert and intercollegiate participants. All of the statistical comparisons described below were made at these six gaze angles. For the intercollegiate participants, two sets of pitches were recorded. The second set of 49 pitches was used for the analyses described here, except for two individuals in which the first set of 49 pitches was used because the second set of pitches did not record properly. The overall data for the intercollegiate participants are plotted in Figure 2.

An analysis of variance was performed on the head rotation values, eye rotation values,

Table 1. Confidence Intervals (Intercollegiate – Non-Experts) and p-Values for T-Tests at Target Angles Along the Trajectory of the Pitched Ball

Required target angle (degrees)	Head rotation	Eye rotation	Gaze error
1.4	95% CI [-1.13, 0.19] p = 0.157	95% CI [-0.13, 1.11] p = 0.117	95% CI [-0.25, 0.44] p = 0.585
2.4	95% CI [-1.84, 0.40] p = 0.198	95% CI [-0.36, 1.57] p = 0.210	95% CI [-0.51, 0.73] p = 0.715
4.1	95% CI [-2.89, 0.67] p = 0.212	95% CI [-0.85, 2.10] p = 0.392	95% CI [-1.12, 1.32] p = 0.868
8.2	95% CI [-6.08, -0.15] p = 0.040	95% CI [-1.54, 3.22] p = 0.472	95% CI [-3.63, 1.07] p = 0.273
16	95% CI [-9.47, -0.80] p = 0.022	95% CI [-5.04, 3.52] p = 0.714	95% CI [-14.41, -3.20] p = 0.004
87	95% CI [-19.24, -4.54] p = 0.003	95% CI [-15.83, -0.32] p = 0.042	95% CI [-31.80, -9.34] p = 0.001

and gaze tracking errors. The factors in these models were participant experience level (non-expert or intercollegiate) and target angle. An interaction term between these two factors was included in the models.

For those data associated with head rotation, all of the factors including the interaction term were significant (p<0.001). For those data associated with eye rotation, target angle (p<0.001) and the interaction term (p<0.003) were significant, while participant experience was insignificant (p=0.15). Finally, for those gaze-tracking-error data, all of the factors including the interaction term were significant (p<0.001).

A two-sample t-test was then used to compare the mean head rotations, mean eye rotations, and mean signed gaze errors of our non-expert participants to those of the intercollegiate baseball players at the six target angles of interest along the pitch trajectory. The level of significance was set at 0.008 to account for the six comparisons associated with each value (head rotation, eye rotation, and gaze error). The results for these comparisons are shown in Table 1.

For those data associated with the head, the only significant difference (p=0.003, 95% CI [-19.24, -4.54] occurred at a target angle of 87˚, at which point the ball had arrived at the batter. At this target angle, the mean head rotation was larger for the non-expert players (26.0 ± 11.0˚) compared to the intercollegiate players (14.07 ± 7.52˚). For those data associated with eye rotation, none of the differences reached significance. For those gaze-error data, significant differences occurred at target angles of 16˚ (95% CI [-14.41, -3.20], p=0.004) and 87˚ (95% CI [-31.80, -9.34], p=0.001). In both cases, the gaze error was larger for the intercollegiate participants (16˚: intercollegiate mean = -6.07 ± 5.73˚, non-expert mean = 2.73 ± 8.45˚; 87˚: intercollegiate mean = -66.39 ± 10.12˚, non-expert mean = -45.82 ± 17.42˚).

Levene's test of equal variance was used to compare the between-participant variability between the non-expert and intercollegiate participant head rotation, eye rotation, and gaze error means at the same six target angles used in the previous analysis. Again, the significance level was set at 0.008 to account for the multiple comparisons. The results are shown in Table 2. There were no significant differences in variance between the non-expert and intercollegiate groups. Given the similarity in the behaviors between the non-expert and intercollegiate groups, it seems that any differences in oculomotor efficiency that may have existed between the two groups did not influence the overall results.

Non-Expert Comparisons

To begin examining whether baseball experience influenced the behavior of the non-expert players, these participants were divided into three groups, and the head rotation, eye rotation, and gaze behaviors were plotted. These groups included High School (n=6, which included those who reported Varsity or

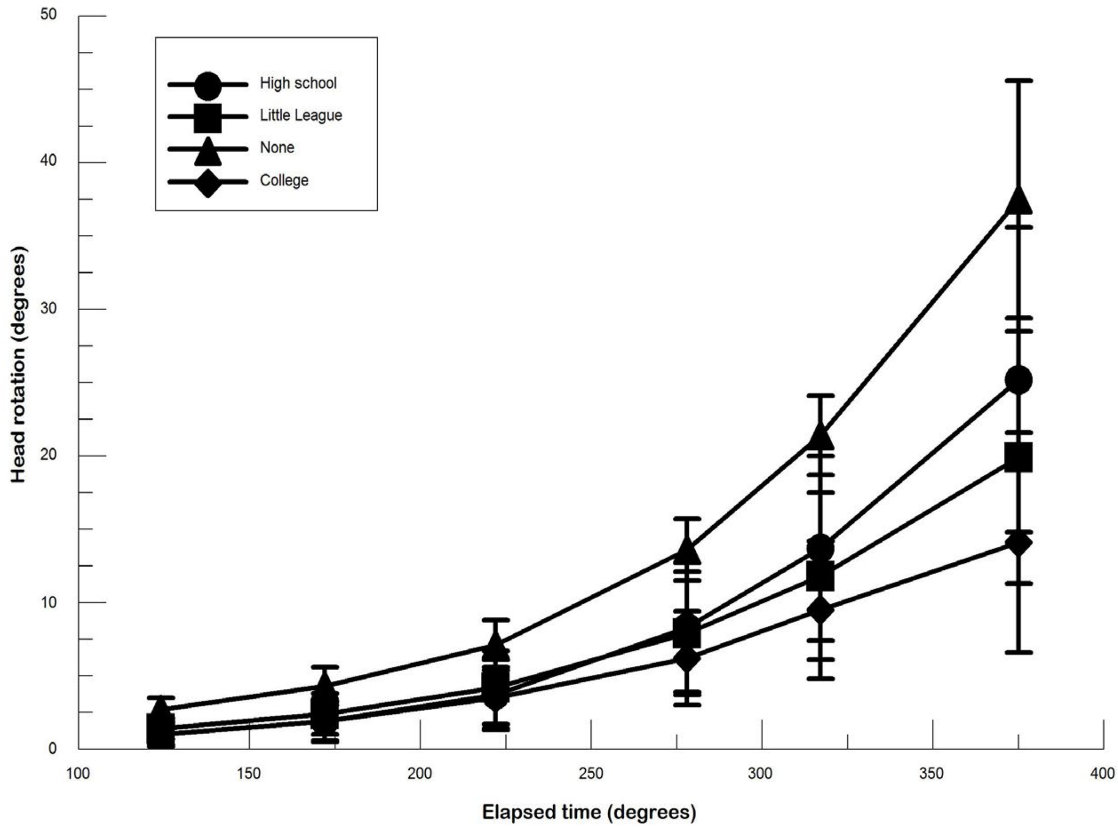

Figure 3. *Head-tracking data (error bars are ±1 standard deviation) for non-expert groups and intercollegiate participants. Those data from the intercollegiate participants have been shifted in time such that data clusters at various elapsed times represent equivalent angles of the ball relative to the participant.*

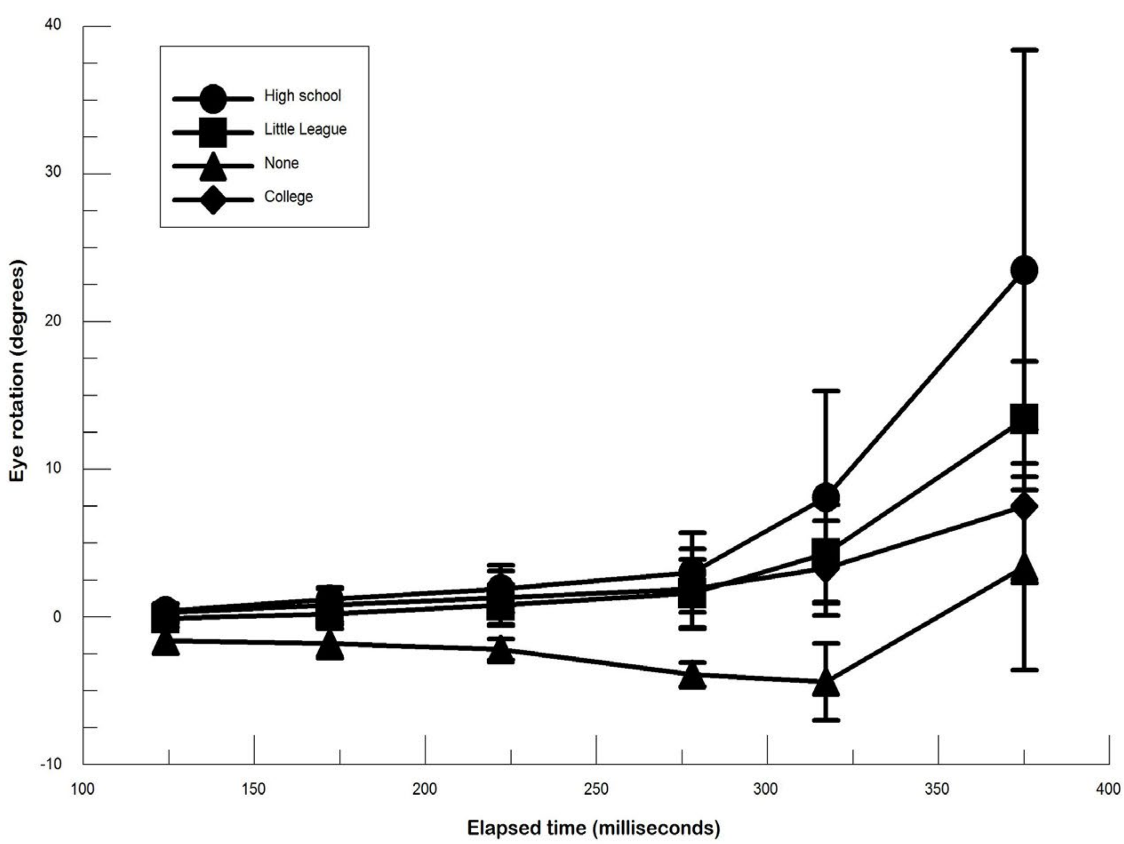

Figure 4. *Eye-tracking data (error bars are ±1 standard deviation) for non-expert groups and intercollegiate participants. Those data from the intercollegiate participants have been shifted in time such that data clusters at various elapsed times represent equivalent angles of the ball relative to the participant.*

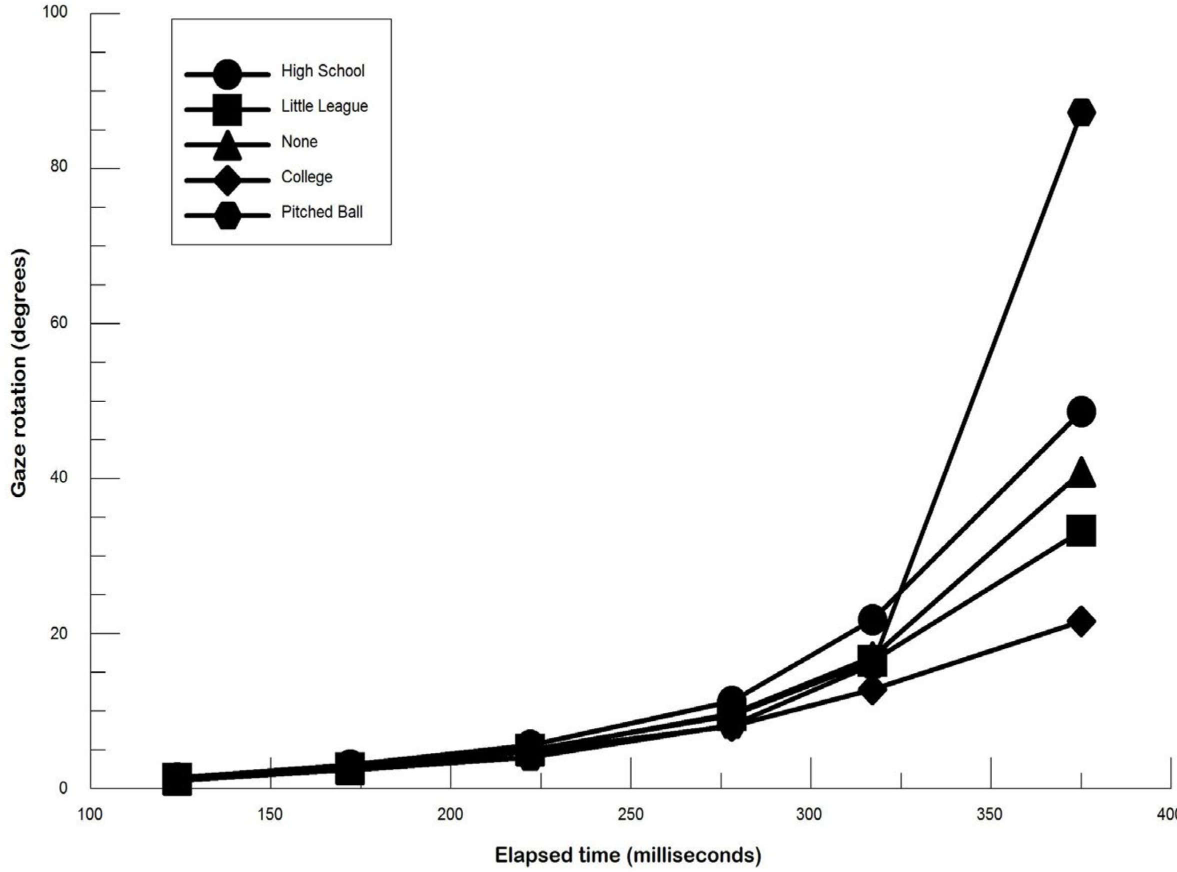

Figure 5. *Gaze-tracking data (error bars are ±1 standard deviation) for non-expert groups and intercollegiate participants. Those data from the intercollegiate participants have been shifted in time such that data clusters at various elapsed times represent equivalent angles of the ball relative to the participant.*

Junior Varsity), Little League (n=5) and None (n=3). The results are shown in Figure 3 (head rotation), Figure 4 (eye rotation in the orbit), and Figure 5 (gaze movement).

While the head and eye movement behaviors were qualitatively similar between the groups, the no-experience group demonstrated both larger head eye movements and larger leftward-going eye movements than the other groups.

Discussion

Visual Cues for Batting

Baseball batters may use a number of cues to accomplish their task successfully. Visual cues that may aid the batter might include such things as the pitcher's grip on the baseball, the pitcher's arm angle upon release of the ball, and the direction of the seams on the baseball when the pitch is released.[12,17,18] Previous studies have shown that expert batters tend to fixate on the pitcher's arm, while less-experienced players may not fixate at this location.[19] This suggests that information regarding the pitch trajectory might be obtained from this source. In the case of the seams on the baseball, Gray demonstrated that the addition of seams in a simulated batting situation improves batting performance,[12] and Gray and Regan[18] demonstrated that the addition of seams influences estimates of the final vertical location of simulated pitches. Better visual acuity would be beneficial for viewing all of these cues.

Eye, Head, and Gaze Tracking Strategies and Batting

In addition to the aforementioned visual cues, other vision-related information may be available to aid in batting. Regarding eye movements and head movements, in the current study, subjects were required to call out numbers and the colors of these numbers on pitched baseballs. It was found that ocular gaze tracking for non-expert baseball batters

Table 2. Confidence Intervals for Standard Deviations of Intercollegiate (IC) and Non-Expert (NE) Participants and p-Values for Levene's Test for Equal Variances at Target Angles Along the Trajectory of the Pitched Ball

Required target angle (degrees)	Head rotation	Eye rotation	Gaze error
1.4	IC 95% CI [0.43, 1.51] NE 95% CI [0.65, 1.68] p = 0.399	IC 95% CI [0.39, 1.22] NE 95% CI [0.49, 2.14] p = 0.438	IC 95% CI [0.29, 0.90] NE 95% CI [0.29, 0.77] p = 0.996
2.4	IC 95% CI [0.76, 2.70] NE 95% CI [1.14, 2.63] p = 0.505	IC 95% CI [0.67, 2.11] NE 95% CI [0.82, 2.80] p = 0.515	IC 95% CI [0.50, 1.56] NE 95% CI [0.50, 1.50] p = 0.921
4.1	IC 95% CI [1.24, 4.13] NE 95% CI [1.88, 4.06] p = 0.395	IC 95% CI [1.17, 3.12] NE 95% CI [1.37, 3.68] p = 0.600	IC 95% CI [1.14, 3.33] NE 95% CI [0.88, 2.54] p = 0.444
8.2	IC 95% CI [2.01, 6.03] NE 95% CI [3.28, 6.92] p = 0.131	IC 95% CI [1.88, 4.48] NE 95% CI [2.36, 6.00] p = 0.461	IC 95% CI [1.91, 4.64] NE 95% CI [1.75, 7.60] p = 0.806
16	IC 95% CI [3.18, 8.41] NE 95% CI [4.84, 9.97] p = 0.119	IC 95% CI [2.03, 5.90] NE 95% CI [4.28, 13.40] p = 0.066	IC 95% CI [4.34, 8.90] NE 95% CI [3.35, 25.43] p = 0.771
87	IC 95% CI [5.16, 13.05] NE 95% CI [7.75, 18.45] p = 0.159	IC 95% CI [3.27, 9.77] NE 95% CI [7.86, 24.60] p = 0.040	IC 95% CI [7.13, 17.10] NE 95% CI [9.48, 38.11] p = 0.273

was maintained throughout much of the pitch trajectory and that the head was generally moved to a greater extent than the eyes. These head rotation, eye rotation, and gaze-tracking strategies were much like those demonstrated previously for collegiate batters who were also asked to name the numbers and colors on pitched balls.[15] Furthermore, although batting was not permitted in the current study, these results are also similar to those that we reported when former collegiate players attempted to bat pitches.[13]

It is of interest to ask whether the head rotation, eye rotation, and gaze-tracking strategies found in the current experiment are likely to provide advantages for batting and whether other tracking strategies would be more appropriate.

First, turning the head at an angular velocity similar to that of the ball maintains the ball in a consistent direction relative to the batter's head and may facilitate batting.[20] This behavior does not necessarily imply that the nose is pointed at the ball (as the absolute starting position of the head was not determined in this study), so the question of whether batters take advantage of the superior encoding of eye position (and therefore target position) provided by less-eccentric eye positions (in the orbit) is yet to be answered.[21] Second, maintaining gaze on the ball increases the time over which visual cues (such as seam orientation) for target trajectory can be processed and could also facilitate future predictions about target trajectory.[4,12,14,22-24] Finally, neural signals associated with efference copy from eye tracking (and perhaps head tracking) may help the batter to estimate when and where the ball will arrive at the plate (i.e., the ball's time to passage), thus aiding batters.[25-28]

Accommodative Facility and Vergence Facility: Influence on Batting

While the contribution of ocular pursuit (and ocular tracking saccades) to batting will be further discussed below, the relative contribution of other eye movement types, as well as ocular accommodation to batting, is also a matter of some interest.[4-6,29] It has been argued that accommodative facility likely does not directly contribute to baseball batting in terms of providing continuous information for estimating when the ball will arrive.[29] This conclusion was derived from known limitations of accommodation. For example, accommodative responses are likely limited for the small amounts of blur of the ball created during the short temporal window over which swing decisions must be made (perhaps 200ms or so after the pitch is released), and further accommodation has a relatively long latency (perhaps 300ms).[29] A similar exercise could be applied to vergence facility and baseball batting. In theory, vergence eye movements could be used to track the baseball as it approaches, or these eye movements might result in a step change in convergence to a location or distance close to the batter. If one were to calculate the change in required vergence angle from the distance at which the pitcher releases the ball (about 55 feet from the batter) to a distance of 50cm from the batter, this change is approximately 7˚. In addition to the latency period that may be associated with this vergence movement (which might be on the order of 160ms or more), such a movement would require over 250ms to complete.[30-32] In total, this vergence movement might require 400ms or more. Given that a 90mph fastball requires about 400ms to traverse a distance from the batter of 55 feet to a distance of 50cm from the batter, a vergence step would bring the eyes to the proper vergence posture around the same time that the ball arrives. The utility of such a step change in vergence for batting is therefore likely to be limited. Further, Bahill and LaRitz[4] found that vergence eye movements did not occur in their baseball ocular tracking study.

On the other hand, there are reports suggesting that athletes demonstrate better vergence facility (which requires step changes in vergence) compared to non-athletes.[6,10] Perhaps vergence facility is correlated with and therefore reflective of the efficiency of other oculomotor functions, including saccades and pursuit.

Ocular Pursuit and Ocular Saccades in Batting (Contributions of Dorsal and Ventral Streams)

Now we return to the question of whether ocular pursuit (or combined eye and head pursuit) provides advantages in estimating when and where an approaching object will arrive and the related question of whether a continuous pursuit strategy or an anticipatory saccade strategy is more appropriate for batting.[4,12] There are studies suggesting that the estimates of when and where an object will arrive are better under pursuit conditions compared to fixation conditions.[22-28] However, it has been argued that the results of studies in which these perceptual estimates have been assessed (as indicated, for example, by a button press upon object arrival but not by an interceptive action) may overestimate the contribution of pursuit to target interception.[33,34]

This argument follows from several lines of evidence. First, the visual system is said to be divided into a ventral stream, whose function is largely to discern the form, color, and identity of objects, and a dorsal stream involved in the perception of depth and motion that sub-serves actions such as target interception.[35-37] Studies in which pursuit eye movements are found to be beneficial for perceptual estimates (which may not engage the dorsal stream) of target time-to-contact or target trajectory may therefore overestimate the influence of these movements (or at least the influence of the neural signals associated with these movements) on interceptive actions (which are largely sub-served by the dorsal stream), such as those in baseball batting.[34] Since the magnocellular system is the primary input to the dorsal stream, and since the magnocellular system is associated with extrafoveal retina,[38,39] it is conceivable that individuals may largely rely on extrafoveal or peripheral cues to visual motion to determine when and where an object will arrive.[25] This reliance on extrafoveal vision could be particularly significant in baseball given that the retinal image of a pitched baseball will increasingly occupy more extrafoveal locations as the ball approaches the batter.[40] Thus, pursuit eye movements may be less beneficial than predicted from studies on perceptual estimates of the spatial and temporal properties of an approaching object when these estimates are not accompanied by interceptive actions.

There is evidence for the significance of the dorsal stream in interceptive actions. For example, Mann et al. performed an experiment in which they demonstrated that low amounts of visual blur (≤+2.00D) had little effect on batting efficiency in cricket.[33] This suggests that the dorsal stream (and therefore extrafoveal motion cues) is in fact controlling target interception in this task. Sasada et al.[34] examined the responses of baseball players as they swung at a virtual (projected) approaching target or pressed a button to coincide with the time at which the target would arrive. At various times along the target's trajectory, the color of the target was changed. The ability of players to identify these color changes was significantly less in the swing condition compared to the button-press condition. This suggests that the ventral stream was relatively more active during the button-press condition, while the dorsal stream was relatively more active during the swing condition.

Other evidence in favor of the significance of the dorsal stream (and by extension, extrafoveal or peripheral motion cues) in controlling interceptive actions comes from studies in which participants exhibit anticipatory saccadic eye movements.[4,12,41] These saccades place fixation ahead of the approaching object, perhaps so that the eyes "lie in wait" for the approaching object rather than tracking this object continuously. Anticipatory saccades place the image of the approaching object in non-foveal locations, where the dorsal stream could potentially process the motion upon which an interceptive action could be based. While this provides a potential explanation for anticipatory saccades, other reasons behind anticipatory saccades (e.g., to gather information about where the object actually arrived[4] or to allow the target to be pursued later in its trajectory[41]) have been proposed.

Lastly, it has been suggested that peripheral or extra-foveal cues (and therefore the dorsal stream) can perhaps improve judgments of eye rotation during pursuit eye movements.[42,43] That is, the retinal image motion of stationary objects in the background during pursuit eye movements may enhance eye rotation signals and therefore enhance estimates of target motion for target interception. Thus, pursuit eye movements may improve target interception not necessarily, or not entirely, because they allow for longer periods over which an object can be observed or because they are associated with neural (efferent) signals sent to the extraocular muscles for these movements. Instead or in addition, pursuit eye movements may contribute to target interception because they induce motion of peripherally viewed stationary structures.

In contrast, there is also evidence against the position that the dorsal stream (and by extension, peripheral or extra-foveal cues) is the predominant controller of interceptive action. First, both Finlay[44] and McKee and Nakayama[45] concluded that while the peripheral visual field can detect motion, the peripheral field is not any more specialized than is central vision for motion.

Second, it has been shown that time-to-contact estimates are processed differently for central and peripheral vision when an object approaches peripherally.[46] In another study, time-to-contact estimates were shown to be less accurate when an object approaches from a peripheral location compared to when the object approaches head-on.[47] However, since both of these studies were based on perceptual estimates rather than interceptive actions, the relevance to baseball batting is unknown.

Third, there are several studies demonstrating that pursuit tracking improves interception of an approaching object even when the background is minimized. For example, Brenner and Smeets[23] asked subjects to intercept a moving target by moving a stylus on a drawing tablet. There appeared to be little detail in the background. These investigators concluded that continuous gaze tracking of the moving target is important for target interception because this allows observers continually to adjust their estimates of the velocity of the target. Other examples include that of Fooken et al.,[24] who demonstrated that the accuracy with which baseball players intercepted a moving dot (with the finger) projected on a screen was correlated with the efficiency of smooth pursuit. The background was relatively unstructured, although the screen was divided into a lighter and darker side, with an apparent border in between. Similarly, Mrotek and Soechting[22] asked subjects to move the hand so as to intercept a target with an index finger as this target moved on a computer monitor. These authors found that subjects tracked the target continuously with the eyes throughout the interception task. Fooken et al.[24] and Mrotek and Soechting[22] argued that continuous pursuit tracking allows for corrections to the trajectory of the hand/finger throughout the interceptive movement. While the extent to which online corrections such as those described in this paragraph might be possible in baseball batting is not clear, these studies, together with our previous study on baseball batting[13] (in which subjects maintained their gaze on the ball throughout the pitch trajectory and did not demonstrate anticipatory saccades), suggest that pursuit eye movements could be beneficial for batters perhaps for reasons not related to signals obtained from the periphery. Rather, pursuit eye movements might provide neural signals related to the trajectory of the ball, or pursuit may facilitate analysis of visual information (e.g., seam direction) derived directly from the ball's appearance.

Lastly, Shapiro et al.[40] demonstrated that the visual periphery is more susceptible than is central (foveal) vision to illusory motion created when an approaching object (such as a baseball) also has internal (rotational) motion. It would seem that accurate pursuit of the pitched ball could to some extent reduce this illusory motion.

In summary, there is evidence that peripheral or extra-foveal motion cues (as likely processed through the dorsal stream) have a significant influence on the efficiency of interceptive actions, while there is other evidence suggesting that pursuit eye movements (and specifically, the neural signals associated with these eye movements) also affect these actions. This leads to the question of which strategy (continuous tracking, as was employed by subjects in the current study, or anticipatory saccades to a location ahead of the approaching object perhaps followed by further continuous tracking) provides the most significant advantage in batting. If this latter question can be answered, then perhaps training regimens could be targeted to those systems (e.g., pursuit or eye/head pursuit in the case of continuous tracking, or saccades in the case of anticipatory saccades) that contribute most to baseball batting.

Summary of Results

In the current study, the overall head rotation and eye rotation behaviors and gaze tracking strategies of the non-expert baseball players were similar to those found for a group of intercollegiate baseball players. The between-participant variability was also similar between the non-expert and intercollegiate groups. For both groups, these behaviors are also similar to those of the Major League Baseball player in the study of Bahill and LaRitz.[4]

These data suggest that the differences in head and eye tracking behaviors between baseball batters with different levels of expertise and experience reported previously may have been at least partially the result of the participants' interpretation of the task and not necessarily related to the participants' level of expertise.

Alternatively, or in addition, it may be that if the current study had included less-predictable pitch velocities, higher pitch velocities, or batting (rather than only ocular tracking), then greater variability in the head and eye movements may have resulted between the non-expert and intercollegiate groups.

Unpredictable pitch trajectories, for example, could make anticipatory saccades more likely as the batter attempts to determine the time and location of pitches upon arrival. This information might then be used in swinging the bat at subsequent pitches. Another possibility is that unpredictable trajectories could then result in inappropriate pursuit responses or anticipatory saccades that would then need to be corrected by further saccades. In this latter situation, differences in response variability between the non-expert and intercollegiate groups could be exacerbated if saccadic efficiency is better for the intercollegiate group. In any event, if unpredictable target velocities lead to more variability in the head and eye movement behaviors of non-expert participants, this may reflect difficulty on the part of the less-experienced batters in estimating when the ball will arrive and not fundamental differences in head and eye coordination from experts. In that case, perhaps training regimens could be aimed at improving batters' estimates of the ball's arrival time rather than at head and eye movements. In support of such training is a study in which collision detection was shown to be improved through training.[48]

In the case of higher pitch velocities, if non-expert participants have slower ocular pursuit velocities compared to expert participants, then non-expert participants might rely more on head movements with these higher pitch velocities or may make use of an anticipatory saccade relatively early in the pitch trajectory in order to allow for pursuit tracking later in the pitch trajectory.[4] In those cases, if it is possible to train participants to increase ocular pursuit velocity, then such training might induce head and eye movement behaviors in non-experts that are more similar to those of experts. There is some evidence that training can improve the efficiency of ocular smooth pursuit.[49]

Finally, one might expect that batting the ball would result in greater variability in the eye and head movements of non-expert batters because of variations in executing the swing of the bat. It should be reiterated, however, that our previous work suggests that tracking and batting tasks result in very similar patterns of head and eye coordination.[15]

When the non-experts were divided by experience level, a difference appeared for the group with no experience. On average, these individuals showed larger head movements (and larger angular velocities) than most of the other individuals, who showed larger eye movements opposite to the direction of the ball. In spite of these differences in head and eye tracking behavior, gaze tracking for this group was similar to that of the other groups. One potential explanation for the pattern of head-eye coordination found in the no-experience group is that these participants are less effective at cancelling the rotational vestibulo-ocular reflex (RVOR) than the other participants.[4] Thus, these participants may have compensated for poor RVOR cancellation by moving the head to a greater extent in the direction of the ball. Given that the RVOR is known to be adaptable,[50] perhaps training of RVOR cancellation could bring about a head and eye coordination pattern in participants with no experience that is similar to that of the other participants in this study. However, since RVOR function was not assessed in the participants, this explanation for differences in head and eye tracking behavior of the non-experts remains speculative.

Conclusion

These results demonstrate that overall, less-experienced baseball batters exhibit a similar pattern of head and eye coordination (greater head movement and lesser eye movement) to that of more-experienced batters. This result suggests that previously reported differences in head and eye coordination for batters with varying levels of experience[4] could have resulted from any or all of the following: differences in interpreting the tracking task, the unpredictable velocity of the pitch, or higher pitch velocities.

Preliminary results also suggest that individuals with no experience in baseball batting demonstrate larger head movements in the direction of the ball and larger eye movements opposite to the direction of the ball compared to individuals with more baseball experience. Further studies with larger numbers of participants will be required to quantify differences in head-, eye-, and gaze-tracking behaviors between non-experts with varying levels of experience, as well as to determine whether the predictability and velocity of the pitch differentially affect gaze-tracking strategy for participants with different levels of experience.

Acknowledgments

This paper is based on a portion of Erik Kuntzsch's work for his Master of Science degree in Vision Science (2017) from the Ohio State University. A preliminary report based on this work was presented as a paper at the 2017 American Academy of Optometry annual meeting. A patent related to the head and eye tracking methodology utilized in this paper is held by the Ohio State University (US Patent #8553936). Nick Fogt is listed as the inventor on this patent, but to date Dr. Fogt has received no royalties related to this patent. This work was sponsored in part by a grant from Optometric Educators Incorporated, Columbus, Ohio.

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Appendix A

In order to assess the noise in the eye-tracker at various angles of ocular rotation, an artificial eye (Figure 6) was employed. This artificial eye consisted of a wooden ball (diameter = 1inch or 25.4mm) to which was attached a 6mm dark spot or "pupil". The ball could be rotated to various angles using a vertical rod placed through the ball. The angle of ball ("eye") rotation was measured using a protractor attached to the top of the vertical rod. The ball was placed within a Styrofoam model head, to which an ISCAN eye-tracker could be attached. Thus, the eye-tracker could monitor rotation of the artificial eye as it rotated within the model head.

Figure 6. *Apparatus used to measure the noise in the ISCAN eye-tracker at various angles of artificial eye rotation.*

The eye was rotated to (and then briefly maintained) at known angles from 35 degrees right to 35 degrees left. At each angle, recordings were made from the eye tracker using an analog-to-digital converter; 2.96 seconds of data from the eye tracker at each angle of rotation were used to calculate the standard deviation of these eye-tracker values. Least squares linear regression of (average) eye-tracker output at each angle versus the angle of rotation was performed to obtain the factor necessary to convert eye-tracker values to degrees of rotation. The standard deviation of the eye-tracker values at each angle of rotation is shown in Figure 7. It is clear that these values were quite small, and none exceeded 10 arc minutes.

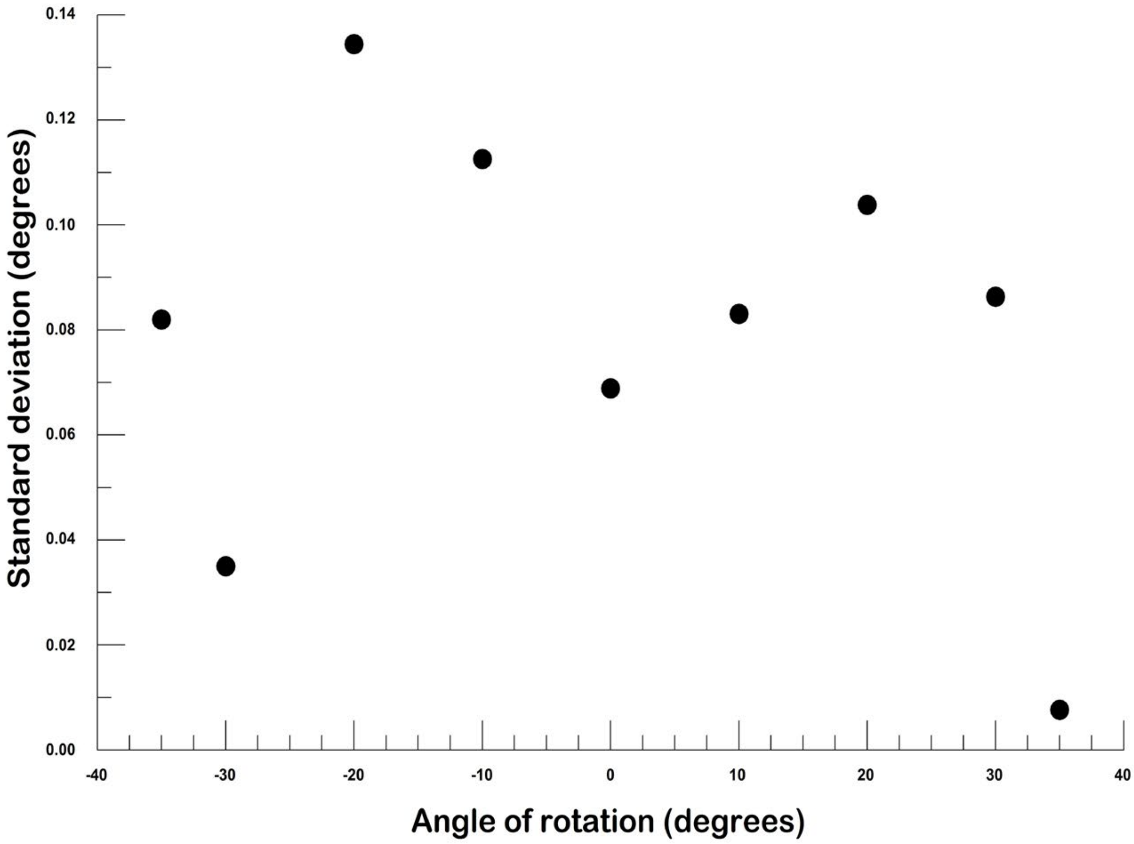

Figure 7. *The standard deviation of measurements taken from the eye tracker versus the angle of artificial eye rotation*