Horizontal and Vertical Eye and Head Movements during a Baseball Swing

THESIS

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Abstract

The purpose of this experiment was to observe and classify the head and eye movements of experienced baseball players when they are trying to hit a baseball. More specifically, it was designed to determine if players track deep into the pitch trajectory when attempting to hit, and if they use a similar tracking strategy when taking a pitch. We hypothesized that the batsmen would utilize two separate tracking methods, one for taking and another for swinging.

Subjects were tested using a pitching machine called the Flamethrower under two separate conditions, in one condition they were instructed to “track the ball like you are taking a pitch”, and in the second condition they were instructed to “swing at the pitches like you would in batting practice”. Tennis balls were pitched from a distance of 56.3 feet from the batter at a measured velocity of approximately 75 miles per hour. Eye movements were recorded with the ISCAN infrared eye tracker and horizontal head rotations were recorded with the 3DM-GX1 head tracker and the Flock of Birds head tracker. All head and eye recordings were temporally synchronized with each other and with ball position using software.

Two subjects were enrolled in the study. Each subject viewed 50 pitches under the “take” condition and 40 pitches under the “swing” condition. A total of 180 pitches were successfully recorded and both subjects were able to track a tennis ball in both testing conditions. Thus, 180 pitches were analyzed.
Mean gaze errors for both trials indicated that the subjects were able to accurately track the pitched tennis balls for a majority of the ball’s flight path under each testing condition. Inter-subject comparison revealed the subjects exhibited similar tracking strategies in each condition, although one subject appeared to have less variability with his head and eye movements.

Both subjects utilized different tracking strategies for taking versus swinging. In the “take” condition, the subjects used fast head and eye movements to produce a tracking lead, in an apparent effort to view the balls when they cross the plate. This observation agrees with previous reports in the literature for a proposed “optimum learning strategy” for successful hitting. In the “swing” condition the subjects used head and eye movements to track the balls late in the pitch trajectory. However, the head and eye movements in the “swing” condition were significantly decreased in both magnitude and amplitude compared to the “take” condition.

Overall, these results indicate that the subjects tracked the balls both horizontally and vertically late in the pitch trajectory when swinging at the pitch. The reason for this is unknown, but indicates tracking with one’s gaze plays an integral role in hitting. That role is yet to be defined, and can only be postulated without further studies.
Dedication

This document is dedicated to my brother, Preston Earl Persson.
Acknowledgments

I would like to thank Dr. Fogt for all of the time and effort he has invested in me and this study. Most importantly, working with him has facilitated me to strive to be a lifelong learner, a more thorough researcher, and a more competent clinician.

I would also like to thank my parents, Preston and Mary Persson, and Marie Schaefer. They have always supported me emotionally and physically through all of my endeavors.
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Fields of Study

Major Field: Vision Science
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Chapter 1: Introduction

1.1: Pitch Dynamics

Hitting a baseball is widely considered one of the most difficult tasks in sport. Porter Johnson, a physics professor at Illinois Institute of Technology was quoted as saying, “If a person from another planet was told what's involved ... they would say it's impossible”\(^1\). To back up his statement, let us break the process down to pitch speed, batter’s reaction time, and flight distance of the ball. Assuming the pitcher releases the ball 5 feet in front the pitcher’s rubber at the apex of the mound, it takes a 90 mile per hour fastball approximately 420 milliseconds (ms) to reach the plate 55 feet away\(^2\). Once initiated, the average major league swing takes 194ms\(^3\), leaving only 200-250ms of in-flight time for the batter to analyze and predict the future location of the ball.

These numbers are mystifying in themselves, leading one to wonder how this can be humanly possible. What physiological mechanisms are at work to allow this to take place? There are a number of physical mechanisms that contribute to successful hitting, including a combination of swing speed, strength, and biomechanics. There is the player’s baseball intellect, or what has been defined as a hitter’s ability to analyze a pitcher’s tendencies, the game situation, the pitch count and the history of previous pitches thrown\(^4\)\(^5\). Finally, there are perceptual or visual cues that could be used to estimate the temporal and spatial aspects of the pitch\(^6\)\(^7\). All of these sources of information could be combined and analyzed to help predict when and where a pitched ball will arrive at the plate.
1.2: Gaze Tracking in Baseball/Previous Studies

The popular notion that a hitter can track a baseball accurately with the eyes from the pitcher’s hand to the plate was apparently derived from a reported claim by Ted Williams, one of the best hitters (statistically) in Major League Baseball history. However, Ted Williams himself, in his book “The Science of Hitting”, explains that it is impossible to track a 90mph fastball through its entire trajectory.5

The original published claim by Williams may be the reason why there is so much emphasis placed on young players to “keep their eyes on the ball.” In fact, apparently in an attempt to encourage tracking behavior, a number of companies and individuals have developed training methods designed to improve a player’s ability to keep their eyes on the ball.8-9. These set-ups make use of a pitching machine to launch balls to which multiple colored dots or multiple numbers have been affixed. There have been a number of reports of professional baseball players using this method to try and improve their hitting.10-11. Some players claim they are able to call out the colors or numbers on a consistent basis, while others actually use the device in batting practice, claiming they are able to pick and choose which pitches to hit based on the color.

A reasonable question is to what extent hitters can in fact accomplish the goal of maintaining foveation during batting, and whether accomplishing this goal provides benefits that are likely to result in better batting.

Ocular gaze tracking in baseball players has been studied in a number of labs, with the most notable studies published by Hubbard and Seng in 1954 and Bahill and LaRitz in 1984. Gaze is used here to indicate the location of the eyes relative to the
outside world (i.e. relative to “space”). Gaze is calculated by adding the rotation of the eye in the orbit to the rotation of the head.

Hubbard and Seng video-taped professional baseball players during batting practice and studied the film to analyze head and eye movements during the pitch. Though not particularly quantitative, this study was the first real look into the ocular gaze tracking methods used by hitters.

In terms of tracking movements during a baseball swing, Hubbard and Seng did not differentiate between horizontal and vertical movements of the eyes and head. They reported that head movements in the direction of the pitched ball were relatively rare during a swing. Tracking eye movements in the direction of the pitched ball were also uncommon, but eye movements were more common than head movements. Tracking eye movements did not become visible until late in the pitch trajectory, and Hubbard and Seng reported that these tracking movements stopped before the batter made contact with the ball (8 to 15 feet in front of the plate)\(^\text{12}\).

Hubbard and Seng interpreted these findings as demonstrating either that the pursuit eye movements were too slow to track the pitch at such high angular velocity, or that the batters had simply given up because they had already initiated the swing and (due to the ballistic nature of the swing) any further visual data collected would be useless. Hubbard and Seng also observed two different methods for tracking, used separately for swinging at a pitch and taking a pitch. They stated that when hitting, players did not utilize head movements as significantly to track the balls to the plate. However, while taking pitches subjects appeared to utilize head movements considerably more\(^\text{12}\).
Bahill and LaRitz performed a second study on eye and head movements in baseball. They used objective equipment including an infrared limbal eyetracker and a series of LEDs on the head monitored by a video camera. Subjects, consisting of (presumably) novice players (graduate students), collegiate baseball players, and one Major League Baseball player viewed a ball pulled toward them with a pulley system that extended from the plate to a distance equivalent to the pitcher’s mound. The pulley system was attached to a motor and was used to accelerate the ball from the pitcher’s mound to the plate, simulating a pitch. The situation was quite unnatural, in that the vertical motion of the ball was minimized and subjects were not allowed to swing a bat at the “pitches”. Because of technical difficulties, complete data (the entire pitch trajectory) were gathered from only 6 pitches and partial data were gathered from another 15 pitches. This illustrates the difficulty of obtaining usable data in such a dynamic and violent research environment.

The major findings in the Bahill and LaRitz study were as follows. First, the professional player made consistent use of equal sized eye and head movements to track the pitches while the other subjects made unequal eye and head movements. The implication appeared to be that there was significant between-subject variability in the novice/less accomplished group of subjects in terms of head and eye movements.

Second, the professional player had faster pursuit/tracking eye movements compared to the other subjects. This subject generated pursuit eye movements that reached speeds of up to 120 degrees/second\textsuperscript{13}. The literature often cites 75 degrees/second\textsuperscript{14} and up to 90-100 degrees/second\textsuperscript{15} as terminal velocity for pursuits. At
higher velocity catch up saccades are generally observed. The data collected by Bahill and Laritz suggests that the professional batsman exhibited higher velocity of smooth pursuit eye movements than what is considered normal, allowing him to track the ball closer to the plate as the angular velocity of the ball increased dramatically. An argument could be made that this subject developed his superior tracking ability at an early age and it contributed to him climbing to the highest level of his sport. Why else is he able track the ball closer than his less skilled peers if the technique was not necessary to perform at the Major League Level?

Third, the professional batter appeared to successfully suppress his rotational vestibulo-ocular reflex (RVOR) as he was able to use both head and eye movements to track the ball to 4 feet. Bahill and LaRitz suggest that some novices may have avoided moving their heads, because of an inability to suppress the RVOR\textsuperscript{13}. The RVOR functions to maintain gaze on an object while rotating one’s head at a high velocity around the y-axis\textsuperscript{16}. For example, rotating the head to the right would stimulate the RVOR, triggering conjugate eye movements to the left. As you can imagine, if a right handed player is rotating their head to the right to follow a pitch, this would stimulate the RVOR, resulting in a saccadic eye movement to the left. The fact that the professional player was able to move their head to the right at high velocity while simultaneously moving his eyes to the right indicates that he was successful in suppressing his RVOR.

So why would it be advantageous for a hitter to use head movements in conjunction with eye movements? The most obvious answer is that using head and eye movements together would effectively increase the velocity of movement possible in the
horizontal meridian. The second, less obvious answer is that humans actually are capable of head rotations comparable in velocity to eye rotations, with rotational speeds around the vertical axis of up to 780 degrees/second\textsuperscript{17}. From this you can see that if a player is able to successfully suppress their RVOR, they could improve their ability to track fast moving objects in the horizontal plane.

Finally, while the professional player tracked the ball accurately (gaze error \(<2\text{deg}\)) until about 5.5 feet in front of the plate, the other subjects tracked the ball accurately only until about 9 feet in front of the plate. Some of the novice/less accomplished subjects did not attempt to track the ball continuously, but rather made a large saccadic movement to a location near the plate\textsuperscript{13}. This saccade was apparently made in an attempt to catch a glimpse of the ball as it crossed the plate. Bahill and LaRitz\textsuperscript{13} and Gray\textsuperscript{4} offer an explanation for this phenomenon, hypothesizing that the batter utilizes this technique to determine the pitch location right before it crosses the plate. They hypothesize that this method is used when taking a pitch and the information collected is then used when swinging at subsequent pitches to facilitate predictions about where subsequent pitches are going to cross the plate.

This anticipatory saccade is in some ways similar to the anticipatory saccades noted in a study of gaze tracking in cricket\textsuperscript{18}. However, it should be noted that the pitch trajectories in baseball and cricket are quite different (the ball bounces in front of the batter prior to contact in cricket) and caution should be used in comparing behaviors between the two sports.
1.3: Why Study Gaze Tracking?

Certainly there is a paucity of quantitative data on eye movements, head movements, and gaze tracking errors in baseball. In addition to the lack of quantitative data on horizontal gaze tracking, there is virtually no vertical gaze tracking data. Finally, while the study of Bahill and LaRitz\textsuperscript{13} suggests that there are likely to be differences between professional players and novices/less accomplished players in terms of both eye and head movements and gaze tracking strategy (and accuracy), these differences may or may not hold up when batters swing at pitches\textsuperscript{19}.

If one were to attempt to predict the gaze tracking behavior of experienced baseball players based on those data from Hubbard and Seng\textsuperscript{12} and Bahill and LaRitz\textsuperscript{13}, one could reach many conclusions. It might be that subjects “give up” tracking prior to the ball reaching the plate. Alternatively these subjects may try to track the ball as long as possible. Finally, subjects may track for a period of time and then make a saccadic eye movement to the end of the pitch trajectory. Given all of these possible outcomes, it is clear that more data are needed on eye movements, head movements, and gaze tracking errors in baseball.

When one discusses gaze tracking, two aspects of this tracking must be considered. First, gaze tracking can be discussed from a motor point of view. In other words, those data generated can simply be used to describe how subjects rotate or move the eyes and the head in order to accomplish the tracking task, and these data can be used to determine the accuracy of gaze tracking.
On the other hand, a second aspect of gaze tracking comes from a sensory point of view. Here, the question that is addressed is why a person may or may not benefit from tracking in baseball. To begin the discussion of sensory aspects of hitting and gaze tracking, it is necessary to examine what aspects of vision may influence batting.

When one attempts to hit a baseball, it is necessary for the batter to estimate the time to collision (TTC) of the ball with the bat so that he or she knows when to swing the bat. The TTC can be estimated from both the expansion rate of the ball as it approaches the batter and the change in retinal disparity of the ball\(^4\,^7\). In addition, the rate of spin of the ball is likely to be valuable in determining pitch speed. One study determined that players were better able to distinguish between a fastball and a curveball when the ball had seams compared to a condition in which the pitched balls did not have seams\(^20\). The subjects in this study apparently used visual cues given by the seam rotation to make a more accurate prediction about the pitch type.

A batter’s static visual acuity may play a role in predicting TTC. This is the type of acuity that is measured during an eye exam with a fixed chart and an immobile patient. One study suggests that experienced hitters’ use static visual acuity to fixate on certain parts of the pitchers body during the release of the pitch\(^21\)-\(^22\), while inexperienced hitters did not focus habitually at any specific point. These investigators suggested that, based on this pattern of fixations, experienced hitters use information about the pitcher’s arm and hand location during ball release to predict the pitch’s trajectory, ball location and speed. If nothing else, focusing in the area of the forearm would most likely help players locate the ball more quickly after it is released by the pitcher.
Static acuity also may be used to evaluate the position of the pitcher’s fingers as he grips the ball, the rotation of the seams upon release, or the angular size of the ball as it approaches the plate\textsuperscript{4,6}. Being able to correctly identify the pitchers grip and the resultant seam rotation could be used to accurately predict what pitch is being thrown. In theory, the seams subtend a large enough angle to be distinguishable at 60 feet.

As mentioned above, determining angular size as the ball approaches the batter may be another important aspect of determining the proposed time to collision\textsuperscript{7}. Subjects are able to evaluate the balls relative rate of expansion and make an estimate of the relative speed of the ball. Determining the rate of expansion would not require an ability to discriminate small angles, as the smallest angle the ball subtends is approximately equivalent to viewing a 20/100 letter at 20 feet.

One would assume that in order to assess these cues most effectively, not only must the subject possess good static acuity, but presumably gaze tracking should be as accurate and as prolonged as possible. In addition to simply providing longer periods of foveation to assess changes in retinal size and retinal image disparity and rotational cues, Matsumiya and Kaneko\textsuperscript{23} have demonstrated that pursuit eye movements improve estimates of TTC, at least in some circumstances.

While estimates of TTC relate to the temporal aspects of the pitch trajectory, the batter must also estimate the final spatial location of the ball. Thus, the batter must address \textit{where} the ball is in terms of its vertical location in space. Bahill and Karnavas\textsuperscript{24} suggested that spatial location could be inferred from pitch speed. That is, a faster pitch will demonstrate a less dramatic vertical drop than a slower pitch. While there are
temporal clues to pitch speed as discussed previously, Gray\textsuperscript{4} has demonstrated that pitch speed is primarily based on predictions made by the batter and derived from such things as the history of previous pitches, the pitch count, and the pitcher’s tendencies.

In support of Gray’s results, Ted Williams attributed the majority of his hitting success to preparation. He stressed the importance of increasing your baseball intellect to the point that you can forecast what pitch you are going to see. This agrees with Williams and Underwood finding that certain pitches are more probable at certain pitch counts\textsuperscript{5}. Having a keen understanding of these tendencies could give a batter an advantage in predicting future pitch trajectories.

Gray\textsuperscript{4} ultimately concluded that the most experienced (and presumably the best) hitters would make use of both prediction (related to the history of previous pitches, the pitch count, and the pitcher’s tendencies) and perceptual/visual cues (ball expansion, retinal disparity change, seam rotation) to make decisions about when and where the ball is likely arrive at the plate. On the other hand, he postulated that less experienced individuals are more likely to be influenced by the history of the previous pitches.

While most agree that prediction plays a large role in successful batting, Gray\textsuperscript{4} suggests that continuous ocular tracking may be more important for more experienced hitters, because experienced hitters may be more adept at using perceptual/visual cues to estimate the temporal and spatial properties of the pitch. However, there are data which suggest that it is only necessary to track a pitch early in the pitch trajectory. This is because 200ms or so after the pitch is released, a batter must begin his or her swing. Therefore, if one assumes that baseball swings are ballistic and cannot be continuously
modified throughout the swing, then all of the perceptual/visual cues mentioned above about the pitch trajectory would need to be assessed very early in the pitch trajectory. Continuous tracking after the swing has begun would be of no benefit.

As mentioned above, Hubbard and Seng\textsuperscript{12} suggested that batters may not track pitched balls all the way to the plate because these hitters gain no benefit from tracking the ball throughout the entire pitch trajectory. Evidence demonstrating the importance of interpreting cues early in the pitch trajectory comes from several studies. Paull and Glencross\textsuperscript{25} demonstrated that expert batters could more quickly and more accurately determine the final location of a pitched ball compared to novices.

In a second study\textsuperscript{26}, cricket batsmen of two different skill levels were studied. The investigators used occlusion goggles to block out visual cues during different parts of a pitches trajectory and then recorded how successful the players were at making contact in each condition. They found that experienced batsmen were better able to utilize pre-bounce (early flight) information to successfully make contact. These results indicate that highly skilled players have a better ability to use prospective data at the beginning of the pitch to more accurately predict where the ball is going to end up, and in effect increase the probability of successful contact.

Adair\textsuperscript{27} sums up the idea that information gathering about pitch trajectory is useless after the swing has begun. He states that one could turn out the lights halfway through a pitch and an experienced batter would perform just as successfully as if the entire pitch trajectory had been seen.
1.4: Summary of Gaze Tracking in Baseball

In summary, there are few quantitative data published thus far on the motor aspects of eye and head movements in tracking a baseball. From a motor point of view, it is not clear how batters make use of eye and head movements in batting, and the length of time over the pitch trajectory during which continuous tracking occurs is also unknown.

It is difficult to speculate on the gaze tracking behavior we are likely to see when a batter swings at the ball. Those limited data from Bahill and LaRitz\textsuperscript{13} suggest that experts track the ball for much of the pitch trajectory, but conclusions from these data are tempered because subjects were not allowed to swing at the ball. Batters most likely need to track the ball initially to assess pitch speed and ball rotation. But does that tracking need to continue once the swing begins? Tracking might continue for most of the pitch trajectory because a baseball swing can be adjusted continuously during the swing (i.e. the swing is not entirely ballistic), or alternatively because tracking throughout the pitch trajectory encourages tracking during the critical early portion of the pitch trajectory. Alternatively, if the swing is ballistic or tracking the pitch throughout the trajectory has little to do with tracking the pitch early in the trajectory, then tracking may not continue throughout the entire pitch.

1.5: Aims of the Study

The focus of our study was to measure eye and head movements when a batter swings at pitched balls, and when that same batter “takes” pitches. In this case, “take” means that the subject knows prior to the pitch that he will not swing at the pitch.
We hope to categorize the movements to better define the role that ocular tracking plays in hitting a baseball.
Chapter 2: Methods

2.1: Subject Enrollment and Eligibility

This study was approved by The Ohio State University Biomedical Institutional Review Board. Written informed consent was obtained from each subject prior to data collection. Objective data were collected on 2 adult male subjects. At the time of the study the subjects were 23 and 26 years of age respectively. The subjects had visual acuities of 20/20 in each eye while wearing contact lenses. Spectacles were not worn in the experiment.

Both subjects had played baseball in college at the NAIA and NCAA Division III level. A fairly objective analysis put the talent of players in the NAIA between NCAA’s Division II and III\textsuperscript{28}. The subjects had both exhausted their eligibility at the college level but were continuing to play in summer baseball leagues with players who had all competed previously at the college level. Both subjects were aware of the aims of this study.

2.2: Pitching Machine

Tennis balls were “thrown” toward the subjects using a mechanical pitching device, appropriately named The Flamethrower\textsuperscript{9}. The Flamethrower uses a rubber bladder to compress air, and uses the energy of the compressed air to repeatedly and accurately launch tennis balls. The pitching machine sits atop a five foot platform ladder with a five foot long polyvinyl chloride (PVC) tube emerging from the device, which is
used to accurately aim the balls. A laser and photodiode were vertically aligned across from each other at the end of the tube closest to the subject to measure the time at which the ball left the tube. The tennis balls broke the plane of the laser when traveling through the tube, causing a drop in voltage from the photodiode (after the photodiode output was routed through an inverting amplifier) which could be measured as described below. Figure 1 contains a photograph of the device.

![Flamethrower with laser and photodiode at end of PVC tube.](image)

**Figure 1.** Flamethrower with laser and photodiode at end of PVC tube.

2.3: Ball Location

2.3a: Linear ball location

Ultimately, we were interested in measuring gaze errors and gaze location of batters at regular intervals over the course of the pitch trajectory. In order to do this, it
was necessary to determine the time required for the ball to traverse a particular linear distance.

We utilized a ballistic timing window\textsuperscript{29} to measure the average time required for the balls to travel a number of distances. We set the timing window up in 12 locations, ranging from about 6 feet to 56 feet from the end of the pitching machine tube, and then attempted to fire 50 balls through the window at each location. Between 47 and 50 pitches successfully passed through the timing window at each of the distances. The times required for each of the pitches to reach a particular location were then averaged and plotted. These data are plotted in Figure 2. Standard deviations/standard errors were not applied to the graph because these values were negligibly small.

![Figure 2. Distance the tennis balls travel vs. time.](image-url)
A second order polynomial was fit to these data. The fitted curve is shown in Figure 2, superimposed on the mean data. The equation for the best fit curve was then used to calculate the linear distance traveled by the ball at any elapsed time after the pitch was released. The average linear velocity of the balls was determined to be 74.97mph.

We chose to determine the eye movement amplitude, head movement amplitude, and gaze position at regular intervals during the pitch trajectory. The elapsed times we specified were 150ms, 200ms, 250ms, 300ms, 350ms, 400ms, 450ms, 500ms, and 512ms. The last value was chosen because this was the mean elapsed time (as determined from the timing window) at which the ball arrived at the plate. We therefore calculated the linear distance traveled by the ball at the elapsed times of interest. These linear distances are shown in Table 1 below.

Table 1. Linear distance of tennis balls from the subjects at specified elapsed times after pitch release, with the associated vertical and horizontal angular subtense (requisite gaze angle for subjects to foveate the ball) at the specified times.

<table>
<thead>
<tr>
<th>Elapsed time (milliseconds)</th>
<th>Linear distance traveled by the ball from curve fit (feet)</th>
<th>Linear distance from subject (feet)</th>
<th>Horizontal angular subtense of ball (deg)</th>
<th>Vertical angular subtense of ball (deg) – down is negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>19.82</td>
<td>36.85</td>
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<td>3.74</td>
<td>-2.17</td>
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<td>14.76</td>
<td>5.75</td>
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<td>46.76</td>
<td>9.91</td>
<td>9.58</td>
<td>-9.10</td>
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<td>450</td>
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<td>512</td>
<td>56.67</td>
<td>0.00</td>
<td>88.01</td>
<td>-55.30</td>
</tr>
</tbody>
</table>
Finally, those data collected from the timing window were used to determine the gaze angle required for our subjects to foveate the target in the horizontal meridian. The calculations shown in Appendix C were used to convert the linear distances of the ball into required gaze angles. The target angle at the plate was not obtained from the curve fit, but rather was set as the known angle necessary to change fixation from the pitching machine to the plate. At the plate, a difference of only a few inches between the actual linear distance traveled by the ball and the linear distance calculated from the curve fit has a significant effect on the required gaze angle calculation. These target angles are shown in Table 1 and Figure 3.

One can see from these data that as the ball approaches the batter, the angular change increases dramatically. In the last 60ms alone the ball travels over an angular distance of 68 degrees. This approximates to an average angular velocity of 1,133 degrees per second over the last 5.5 feet of the ball’s trajectory.
Figure 3. Horizontal target angle vs. time.

2.3b: Flamethrower accuracy/Vertical ball location

The positional accuracy of the Flamethrower was determined by firing tennis balls against a sheet of plywood covered with a white piece of paper at 6 different distances, as seen in Table 2. Ten or eleven balls were fired at each distance. The balls left a slight mark on the paper making it possible to measure the approximate grouping and average distance from the ground at each specified location. Figure 4 provides a visual representation of the data in Table 2, demonstrating the distance a pitch drops when travelling from the mound to home plate.
Table 2. Pitch height and grouping at six locations between the pitching machine and home plate.

<table>
<thead>
<tr>
<th>Distance from Pitching Machine (ft)</th>
<th>Vertical height (inches)</th>
<th>Standard Error Vertical (inches)</th>
<th>Horizontal Spread (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>64.53</td>
<td>0.70</td>
<td>3.5</td>
</tr>
<tr>
<td>20</td>
<td>64.27</td>
<td>0.27</td>
<td>4</td>
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<tr>
<td>30</td>
<td>59.52</td>
<td>0.76</td>
<td>5</td>
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<tr>
<td>40</td>
<td>54.50</td>
<td>1.30</td>
<td>6</td>
</tr>
<tr>
<td>50</td>
<td>42.22</td>
<td>1.31</td>
<td>9</td>
</tr>
<tr>
<td>55</td>
<td>33.90</td>
<td>1.80</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 4. Vertical drop of tennis balls as they approach home plate (with standard error).

The data in Table 2 shows the balls drop an average of 30 inches from the release point until crossing the plate 56.3 feet (676 inches) away. A curve was fitted to these data, and the equation describing this curve was utilized to calculate the vertical location of the ball during selected times in the pitches trajectory.
Those calculations used in determining the required vertical gaze angles are shown in Appendix D, and the resultant data are shown in Table 1. It should be noted that the vertical change in gaze angle must be calculated by factoring in the linear distance of the batter from the ball.

2.3c: Summary of ball location measurements

The measurements of horizontal and vertical location of the ball throughout the ball trajectory were very consistent. Thus, we felt that it was appropriate to simply monitor the time at which the ball exited the pitching machine using the photodiode/laser combination at the end of the pitching machine tube. Then, the gaze position of the subjects during the pitch was compared to the average angular position of the ball in Table 1 at the elapsed times of interest.

2.4: Eye and Head Movement Monitoring

2.4a: Monitoring eye movements

All batters stood in the right handed batter’s box. Eye position was recorded from their lead eye (left eye) which was closer to the pitching machine. Eye movements were monitored using infrared video recording goggles manufactured by ISCAN Incorporated (Burlington, MA) in Figure 5. The ISCAN goggles work by tracking the center of the subject’s pupil to detect both horizontal and vertical eye movements. The infrared cameras are mounted above the eye to monitor pupil position as the image of the eye is reflected off beam-splitters which are mounted just below the eyes. The estimated spatial resolution of the ISCAN is 15 minutes of arc and the camera speed is 120 Hz. In a
separate experiment, the overall accuracy of the ISCAN was determined to be within 0.13 degrees of the search coil (Appendix A).

Figure 5. ISCAN goggle. The infrared cameras are oriented vertically aimed down toward the clear lenses (beam splitters). The Flock of Birds head-tracker (receiver) is mounted directly between the two infrared cameras but in the experiments, the receiver was mounted on top of the helmet close to the Microstrain head-tracking device.

The output from the ISCAN is recorded in digital format and for analysis it was fed through a digital-to-analog converter (USB 1208FS, Measurement Computing, Norton, MA) for recording. To determine the horizontal amplification or gain of the ISCAN, subjects were instructed to fixate a small target attached to the batting cage in front of the subject while maintaining a fixed head position. They then fixated a small
target just below the pitching machine (which was 56.3 feet from the subject), again maintaining a fixed head position. The subsequent horizontal angle between the two fixation targets was 51.1 deg. The ISCAN digital values for each subject were recorded at each of the fixation positions and an average gain was calculated and used for analysis. Therefore, gain = (ISCAN digital value at pitching machine – ISCAN digital value at near location)/(51.1 deg).

To determine the vertical amplification or gain of the ISCAN, the subject turned his body such that his face was parallel to the batting cage in front of him. Two small fixation targets, separated vertically, were affixed to the batting cage. These two fixation targets required a change in vertical angle of 26.6 deg. While the subject maintained his head in the same position, he fixated one target and then the other target. The ISCAN digital values for each subject were recorded at each of the fixation positions and an average gain was calculated and used for analysis in the same way as the horizontal gain was calculated.

2.4b: Monitoring head movements

Head movement was monitored using two devices. Both head trackers were attached to the top of the batting helmet worn by the subjects. This is because one tracker (Model 3DM-GX1, Microstrain, Williston, VA) was very accurate temporally, while the other tracker (Flock of Birds, Ascension Technology Corporation, Burlington, VT) allowed us to measure head movement using six degrees of freedom. These six degrees
of freedom are anterior-posterior translation, horizontal translation, vertical translation, horizontal rotation, vertical rotation, and tilt (rotation to the shoulder).

The temporal delay of the Microstrain head tracker was assessed in the following way. The Microstrain was attached to a wooden device that could be rotated horizontally (Figure 6). A laser was mounted on the same device, such that when the entire device was rotated, the Microstrain and laser were rotated together. Next, the laser was aimed at a photodiode. Finally, the entire device to which the laser and Microstrain device were attached was rapidly rotated, such that the laser was no longer aimed at the photodiode. This resulted in a change in the photodiode outputs. By monitoring the analog output from the photodiode and the analog output from the Microstrain head tracker using an analog-to-digital converter, it was possible to determine whether there was a temporal delay in the Microstrain device. Sixteen measurements were made, and the average temporal delay in the Microstrain device was determined to be 7.2 ± 3.8ms.

Figure 6. Device for measuring temporal accuracy of Microstrain.
The Flock of Birds is a magnetic tracker. It consists of a transmitter that generates a DC magnetic field, and a receiver. The receiver was attached to the top of the helmet worn by the subject. The Flock of Birds receiver passes data to the computer through a serial port that was in a different computer from that used to measure voltages from the ISCAN eyetracker, the Microstrain, and the photodiode at the end of the pitching machine tube. The Flock of Birds data are recorded at a sampling rate of approximately 56Hz. The accuracy of the Flock of Birds was assessed as described in Appendix B. The computer containing the serial port through which the Flock of Birds data were fed, also contained an analog-to-digital converter (CIO-DAS08, Measurement Computing, Norton, MA). This analog-to-digital converter ran continuously at 2000Hz while the Flock of Birds data were recorded, and thus this analog-to-digital converter allowed us to place a time stamp on those data from the Flock of Birds.

2.4c: Summary of data recording

In summary, two computers were utilized to record those data from the various sensors in this experiment. In one computer, an analog-to-digital converter (USB-1208FS, Measurement Computing, Norton, MA) was used to record analog voltages from the ISCAN, the Microstrain head tracker (horizontal rotation only), and the photodiode (routed through an inverting amplifier) in the laser/photodiode combination at the end of the pitching machine tube. These analog data were recorded in synchrony at 2000Hz (each input was recorded at 2000Hz) using a program running in Visual Basic 6.0 (Microsoft Corporation, Redmond, WA).
In a second computer, the 6 degrees of freedom (3 translational/linear values and 3 rotational values) data from the Flock of Birds were recorded through a computer serial port at approximately 56Hz. A customized computer program was used to record both the Flock of Birds data and at the same time a time stamp (2000Hz) from an analog-to-digital converter (CIO-DAS08, Measurement Computing, Norton, MA) located in the same computer. Because data were recorded in two separate computers, combining these data (as will be described in the results) was quite time-consuming.

2.5: Translation Error of Flock of Birds

The translational (linear) values obtained from the “Flock of Birds” instrument required correction because of the distance of our subjects from the transmitter. In our study the batters were approximately 51 inches from the transmitter, which was necessarily placed outside of the batting cage. As the receiver (attached to the top of the helmet) is moved further from the transmitter there is a measurement error; specifically, the units measured decrease in magnitude the further the receiver gets from the transmitter. If one were to move the receiver over a distance of one foot at 12 inches from the transmitter, and one foot at 48 inches from the transmitter two different measurements would result. The measurement recorded at 48 inches is less than that at 12 inches by a significant amount.

To quantify the magnitude of this distance-related error we measured horizontal and vertical linear movement at two feet and four feet from the transmitter. At each distance the receiver was moved over a horizontal distance of 24 inches and a vertical
distance of 12 inches (independent of each other). Figure 7 represents the measurements taken in the horizontal plane.

![Graph showing horizontal translation](image)

Figure 7. Horizontal translation as recorded by Flock of Birds at 2 feet and 4 feet from the receiver.

As you can see, the measurement at two feet from the receiver, (corresponding to the first two waves in the figure) measured a total wave height of around 24 inches, correlating nicely with the actual movement of the receiver. In the second measurement, taken at four feet, you can see that the instrument measures a total movement of 16 inches. This was significantly less than the actual distance moved by the receiver. We used the difference between the two to determine a correction factor since our subjects were approximately 51 inches from the receiver during data collection.
It is important to note that anterior/posterior translation was measured during testing, but was not factored into the final calculation of gaze position. We determined that the anterior and posterior translation of our subjects would not significantly impact the target angle of the balls (this translation was in all cases less than 2 inches away from the anterior-posterior location of the head at the beginning of the pitch), and would therefore minimally affect our gaze error calculations.

2.6: Study Construct

The study was designed to accurately monitor and record vertical and horizontal head and eye movements under two conditions. The study was carried out in a batting cage at the Adventure Recreation Center, on campus at The Ohio State University in Columbus, Ohio, with permission of the Department of Recreation Sports at Ohio State.

Subjects were set up in one end of the batting cage, with a tight fitting baseball helmet secured using a chin strap and equipped with a fitted metal cage to protect the face. The ISCAN goggles were worn underneath the cage to monitor eye movements. The Microstrain sensor and Flock of Birds receiver were mounted on the top of the helmet. Subjects were set up in a batter’s box with their back (right) foot lined up with the back corner of the plate. The measured (anterior-posterior) distance of the subjects from home plate was 23.5 inches. The Flamethrower pitching machine was set up inside the batting cage, 676” (56.3 feet) from the batter.

The study was divided into 2 distinct conditions in which tracking for each subject was monitored. In the first condition, the two subjects were told to behave as if they were “taking” pitches. “Taking” is the baseball term used when a batter does not
swing, or in our case does not intend to swing, at the ball. Fifty pitches were thrown to the subjects in this condition. In the second condition the subjects were told to try and hit the balls. In the first condition, the eye tracker was calibrated (in both the horizontal and vertical directions) once prior to firing the 50 pitches. The eye tracker was calibrated twice in the second condition; once prior to the first 20 pitches and again prior to a second group of 20 pitches. Multiple calibrations were performed in the second condition in case the equipment had moved when the subjects were swinging. The calibration factors were similar between the first and second 20-ball swing conditions.

The initial 50 balls (“take” or non-swinging condition) were shown to the subjects in order for them to become accustomed to both the study equipment and to spotting the balls as they exited the pitching machine. This is similar to when a batter “times” a pitcher prior to taking their place at the plate. The instructions given to the subjects in the first condition were, “Track the ball like you are taking a pitch.” The pitches were separated in time by approximately 3 to 5 seconds and all 50 tennis balls were fired consecutively from the pitching machine.

In the second condition, eye and head movements were tracked while the subjects were trying to hit the tennis balls. Their instructions were to, “Swing at the pitches like you would in batting practice.” Each subject was given an opportunity to hit 40 balls, but in comparison to the first condition, balls were not fired as rapidly, averaging five to seven seconds between pitches. The additional time in the second condition was put in place to allow the batter to reset their stance and prepare for the next pitch.
Furthermore, the 40 pitches that the players swung at were broken up into four sets of ten. A 30 second rest period was given between sets one and two, and between sets three and four. The rest periods were implemented to give the subjects a brief time to rest, so their biomechanics remained relatively consistent with each pitch.

Under the swinging condition the quality and type of contact was visually monitored and described in an attempt to monitor the success of the subjects. Table 3 contains the descriptive values that were used to quantify the contact made. The “field of play” was loosely termed to describe a batted ball that stayed between the projected first and third base paths from our batsmen.

Table 3. Grading criteria describing quality of bat/ball contact.

<table>
<thead>
<tr>
<th>Solid Contact</th>
<th>Good Contact</th>
<th>Mild Contact</th>
<th>No Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hard Groundball</td>
<td>1. Pop up in field of play</td>
<td>1. Any contact not in field of play</td>
<td>1. Swing and miss</td>
</tr>
<tr>
<td>2. Line drive in</td>
<td>2. Weak groundball in field of play</td>
<td></td>
<td></td>
</tr>
<tr>
<td>field of play</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 3: Results

3.1: Data Analysis

Prior to discussing these data analyses in detail, it should be noted that we did not measure the absolute position of the head (relative to the body) at the beginning of each pitch. The head position at the beginning of each pitch was simply zeroed, so the head rotation we are reporting is the rotational change from the beginning of the pitch to our elapsed times of interest.

Similarly, the eye tracking data were also zeroed at the beginning of the pitch. Thus, we implicitly assume that the subjects are looking at the location where the ball is released (i.e. the pitching machine tube) at the beginning of the pitch.

3.1a: Synchronization of those data from the Ascension Flock of Birds data and those data from the analog-to-digital converter

A major goal in analyzing these data was to temporally synchronize those data from the Ascension Flock of Birds with those data from the laser/photocell detection device at the end of the pitching machine tube and the ISCAN eye tracking data. The Ascension Flock of Birds provided three values for head rotation (horizontal, vertical, tilt) and three values for linear motion or translation (anterior-posterior, horizontal and vertical). Therefore, we chose to use the Ascension Flock of Birds to determine the location of the head.
Those (horizontal) data from the Microstrain head tracking device were very noisy. Thus, these data were run through a low pass filter (10Hz cut-off) using a computer program (Psi-Plot, Poly Software International). The filtered analog-to-digital recordings from the Microstrain head tracking device and the synchronized recordings from the laser/photocell ball detection device were then passed through a custom computer program that performed several functions. First, this program applied a forty point averaging filter to the already low-pass filtered Microstrain data. Next, the program identified those times when the tennis balls exited the pitching machine. Finally, the program calibrated the Microstrain data using a calibration factor measured previously and divided these data up into individual data files covering two seconds of data. These data sets began at the time those data from the laser/photocell detection indicated that a pitch had been released and continued for two more seconds.

All of those horizontal data from the Ascension Flock of Birds were plotted. On a separate graph, those data from the photocell/laser and those data from the Microstrain head tracker were plotted together. By comparing the Ascension Flock of Birds plot to the photocell/laser and Microstrain plot, we could manually parse those head movement data from the Ascension Flock of Birds that were associated with each pitch.

Once the data from each pitch were parsed manually (Ascension Flock of Birds) or by the computer program (Microstrain) they could be plotted together on the same two-dimensional graph. The Microstrain data and Ascension Flock of Birds horizontal position data were each plotted against their own unique time stamp. The time stamp
associated with the Flock of Birds came from an analog-to-digital converter (2000Hz) recorded along with those data from the Flock of Birds. The time stamp associated with the Microstrain head tracker was known from the recording rate set for the analog-to-digital converter (2000Hz) into which these data were recorded. The time stamp for the Microstrain head tracker was adjusted for a 7ms lag that was measured as described in the methods.

Once the Microstrain and Flock of Birds recordings were plotted against their respective time stamps for each pitch then the Flock of Birds data were shifted in time to match those data from the Microstrain. For those data associated with “taking” pitches, the Microstrain and Flock of Birds data were matched according to the time at which a head movement in the direction of the ball (i.e. to the right) was seen to begin.

On the other hand, for those data associated with “swinging” at pitches, it was found that the Microstrain and Flock of Birds data were most efficiently matched temporally according to the time at which the head movement changed from a rightward to a leftward movement. The leftward movement was presumably associated with the swing.

Next, we made a determination as to whether the Microstrain data and the Flock of Birds data demonstrated a high degree of temporal and spatial coherence. Those data in which coherence could not be established were discarded. After this exercise, for the “take” condition 25 pitches were analyzed for Subject 1 (it may have been possible to analyze more) and 13 pitches were analyzed for Subject 2. For the “swing” condition, 23 pitches were analyzed for Subject 1 and 13 pitches were analyzed for Subject 2.
Finally, once the Microstrain and Flock of Birds horizontal tracking data were matched in time and those data to be analyzed were chosen, the beginning of each Flock of Birds data file was zeroed. It was then possible to go into the Flock of Birds data columns and find the head translation (horizontal and vertical) and head rotational values (horizontal, vertical, tilt) values at elapsed times of interest. Again, these elapsed times of interest were 150ms, 200ms, 250ms, 300ms, 350ms, 400ms, 500ms, and 512ms.

3.1b: Eye values

The ISCAN eye tracker reports the position of the eye relative to the orbit. The horizontal and vertical analog-to-digital recordings from the ISCAN eye tracker and the synchronized recordings from the laser/photocell ball detection device were passed through the same custom computer program that was used to analyze those data from the Microstrain device. This program identified those times when the tennis balls exited the pitching machine. Then, the program calibrated the eye tracker data using the calibration factor measured in the experiment. Finally, the program divided these data up into individual data files covering two seconds of data. These data sets began at the time those data from the laser/photocell detection indicated that a pitch had been released and continued for two more seconds.

Once these eye tracker data were divided into individual pitches, it was necessary to shift them temporally to account for the recording delay of the eye tracker (Measured as described in Appendix A). After these data were shifted temporally, then the beginning of the data files was zeroed. Finally, we were then able to go into these data files and
manually extract the horizontal and vertical eye movement locations at our elapsed times of interest.

3.1c: Gaze values

The horizontal and vertical gaze values (eye position in space) allowed us to compare the fixation position of the eyes to the location of the ball at our elapsed times of interest during the pitch trajectory. The gaze values were calculated by adding the eye tracker rotational values to the head tracker rotational values at the elapsed times of interest (pre-corrected gaze angles). Next, horizontal and vertical translation was factored in as described in Appendix E and Appendix F to obtain the corrected horizontal and vertical gaze angles respectively. As discussed in Appendix G, head tilt causes a small artifact in the horizontal and vertical eye movement measures. These artifacts were not compensated for as they did not change the conclusions of the study.

3.2: Head Movement Behavior

3.2a: Horizontal head rotation

Figure 8 shows six graphs of horizontal head rotation for both subjects in each condition (“take” and “swing”). The first four graphs demonstrate that both subjects exhibited significantly less variability in horizontal head rotation when taking pitches. These results suggest that it is more difficult to consistently produce the same control of head rotation from pitch to pitch when one swings a bat.
These graphs also demonstrate that head movement amplitudes were substantially larger later in the pitch in the “take” condition compared to the “swing” condition. The difference was larger for Subject 1 than for Subject 2.
Figure 8. Graphs 1 and 2 (positive is towards the plate) are the horizontal head movements for Subject 1 under each condition. Graphs 3 and 4 are the head movements for Subject 2 under each condition. Graphs 5 (Subject 1) and 6 (Subject 2) serve as a comparison of the mean horizontal head rotation between conditions.
3.2b: Vertical head rotation

Figure 9 shows six graphs of the vertical head rotation for each subject in both conditions. The first four graphs in the figure are used to subjectively compare the subjects’ variation under each condition. Much like those graphs associated with horizontal head rotation, these data demonstrate that subjects exhibit significantly less variability and smoother head movements when they are taking a pitch compared to the situation where they are swinging at pitches. Furthermore, it is of interest to note that the vertical head movements of both subjects continue toward the plate even late in the pitch trajectory in both the take and swing conditions.

In Graph 5 and 6 (Figure 9) one can see that the subjects appeared to utilize similar tracking strategies in the vertical meridian for both the “take” and “swing” conditions. The major difference between the “take” and “swing” graphs is the slight upward rotation exhibited by both subjects at the 0.30-0.35s mark in the “swing” condition. This upward deflection is most likely associated with the beginning of the swing.
Figure 9. Graphs 1 and 2 (negative is down) are the vertical head movements for Subject 1 under each condition. Graphs 3 and 4 are the head movements for Subject 2 under each condition. Graphs 5 (Subject 1) and 6 (Subject 2) serve as comparison of the mean head rotation in each condition.
3.2c: Head tilt

In Figure 10 there are two graphs representing the mean head tilt of each subject under both conditions. From Graph 1 and 2 (Figure 10) it is evident there is significantly more head tilt when the subjects are swinging, compared to taking.

Figure 10. Graph 1 (positive is towards the right shoulder) is the mean tilt of Subject 1's head under both conditions. Graph 2 is the mean tilt of Subject 2's head under both conditions.

3.3: Eye Movement Behavior

3.3a: Horizontal eye rotation

Figure 11 contains six graphs comparing horizontal eye rotation in the “take” and “swing” conditions. In comparing graphs 2 and 4 (swing condition), it is apparent that Subject 1 demonstrates less variability than Subject 2. Table 4 contains the standard error of the mean at specific elapsed times for the horizontal eye rotation in the swing condition. Subject 1 is markedly more consistent, particularly late in the pitch trajectory.
Table 4. Standard error of horizontal eye rotation.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Standard error of Subject 1 (degrees)</th>
<th>Standard error of Subject 2 (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.150</td>
<td>0.199</td>
<td>0.314</td>
</tr>
<tr>
<td>0.200</td>
<td>0.236</td>
<td>0.340</td>
</tr>
<tr>
<td>0.250</td>
<td>0.228</td>
<td>0.251</td>
</tr>
<tr>
<td>0.300</td>
<td>0.217</td>
<td>0.348</td>
</tr>
<tr>
<td>0.350</td>
<td>0.289</td>
<td>0.522</td>
</tr>
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<td>0.400</td>
<td>0.369</td>
<td>0.692</td>
</tr>
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<td>0.450</td>
<td>0.413</td>
<td>1.030</td>
</tr>
<tr>
<td>0.500</td>
<td>0.469</td>
<td>1.230</td>
</tr>
<tr>
<td>0.510</td>
<td>0.466</td>
<td>1.060</td>
</tr>
</tbody>
</table>

In both conditions, both subjects demonstrate a leftward-going eye movement (toward the pitching machine). This movement is typically seen about 0.35s after the pitch is released for Subject 1 and about 0.40s after the pitch is released for Subject 2. This is most likely the result of activation of the RVOR as the head begins to move substantially at those times. This is similar to what Bahill and LaRitz reported in their 1984 study. Despite intrusion of the RVOR, rightward eye movements are again initiated in spite of the ongoing head movement, indicating cancellation of the RVOR.

Looking at mean eye movements in graphs 5 and 6 (Figure 11), it is clear that the eye rotations are vastly different between the “take” and “swing” conditions. In the “take” condition, the eyes show a very large movement relatively late in the pitch trajectory. In the “swing” condition, the eyes show very little movement throughout the pitch trajectory.
Figure 11. Graphs 1 and 2 (positive is towards the plate) contain the horizontal eye movements for Subject 1 in the take and swing conditions, respectively. Graphs 3 and 4 represent the horizontal eye movements for Subject 2 in the take and swing conditions, respectively. Graphs 5 and 6 compare the mean intra-subject variability of horizontal eye movements for each condition.
3.3b: Vertical eye rotation

Figure 12 contains six graphs for vertical eye movements in the two conditions. Comparing eye movements in graph 2 and 4 (swing condition), it is again apparent that Subject 1 demonstrates less variability in his vertical eye movements than Subject 2. This is similar to the horizontal eye rotation performance in the swing condition for our subjects. Table 5 contains the objective standard error calculations for the subjects at each elapsed time.

Table 5. A comparison of the standard error of vertical eye rotation between subjects 1 and 2.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Standard error of Subject 1 (degrees)</th>
<th>Standard error of Subject 2 (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.150</td>
<td>0.138</td>
<td>0.367</td>
</tr>
<tr>
<td>0.200</td>
<td>0.192</td>
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<td>0.250</td>
<td>0.208</td>
<td>0.540</td>
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<td>0.300</td>
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<tr>
<td>0.510</td>
<td>0.853</td>
<td>1.320</td>
</tr>
</tbody>
</table>

Graphs 5 and 6 (mean vertical eye movement values) in Figure 12 demonstrate the variance in tracking methodology between the “take” and “swing” conditions for our subjects. In the “swing” condition both subjects drop the eyes well below the target, while in the “take” condition the subjects maintain the eyes close to the target for a longer period of time. Interestingly, the strategy used by each subject while swinging appears to be similar in shape, but different in magnitude.
Figure 12. Graphs 1 and 2 (negative is down) contain the vertical eye movements for Subject 1 in the take and swing conditions, respectively. Graphs 3 and 4 represent the vertical eye movements for Subject 2 in the take and swing conditions, respectively. Graphs 5 and 6 compare the mean intra-subject difference of vertical eye movement strategy for each condition.
3.4: Gaze Position

3.4a: Horizontal gaze position

Figure 13 shows the mean horizontal gaze position for Subject 1. In this figure it is evident that the subject utilizes two separate tracking strategies for the “take” and the “swing” conditions. The line with the yellow triangles represents the target angle, or the viewing angle required for the subject to foveate the ball. The first strategy is denoted by the green circles and represents the mean gaze position in the “take” condition. A tracking lead is evident late in the trajectory in the “take” condition. Indicating Subject 1 is actually looking in front of the ball during the last portion of the pitch trajectory, and his gaze location intersects with the ball’s location at or near the time the ball reaches the plate.

The gaze tracking strategy for Subject 1 in the swing condition is denoted by the red squares. Unlike the gaze tracking strategy employed by this subject in the “take” condition, in the “swing” condition the subject’s gaze remains close to the ball until an elapsed time of about 0.45s. The lack of obvious error bars associated with those gaze tracking data in the swing condition demonstrate the very small standard errors of these means.
The gaze tracking positions in the “take” and “swing” conditions for Subject 2 are shown in Figure 14. The green circles represent his gaze tracking position in the “take” condition. Much like Subject 1, in the “take” condition Subject 2 exhibits a significant tracking lead late in the pitch trajectory. On the other hand, in the “swing” condition, gaze tracking remains close to the ball until late in the pitch trajectory.
Figure 14. Mean horizontal gaze angle of Subject 2 with associated standard error bars.

Tables 6 and 7 below show the horizontal gaze errors (as calculated from the mean gaze errors) for Subjects 1 and 2 in the “take” and “swing” conditions.
Table 6. Horizontal gaze errors (degrees) in the "take" and "swing" conditions for Subject 1. Negative indicates a gaze lag (eyes to the left of the ball).

<table>
<thead>
<tr>
<th>Elapsed time (milliseconds)</th>
<th>Horizontal gaze error (&quot;take&quot;)</th>
<th>Horizontal gaze error (&quot;swing&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>-0.87</td>
<td>0.49</td>
</tr>
<tr>
<td>200</td>
<td>-1.30</td>
<td>0.18</td>
</tr>
<tr>
<td>250</td>
<td>-1.88</td>
<td>-0.82</td>
</tr>
<tr>
<td>300</td>
<td>-2.62</td>
<td>-3.94</td>
</tr>
<tr>
<td>350</td>
<td>-3.14</td>
<td>-5.73</td>
</tr>
<tr>
<td>400</td>
<td>3.88</td>
<td>-3.86</td>
</tr>
<tr>
<td>450</td>
<td>24.81</td>
<td>-3.09</td>
</tr>
<tr>
<td>500</td>
<td>7.41</td>
<td>-52.81</td>
</tr>
<tr>
<td>512</td>
<td>-3.70</td>
<td>-72.74</td>
</tr>
</tbody>
</table>

Table 7. Horizontal gaze errors (degrees) in the "take" and "swing" conditions for Subject 2. Negative indicates a gaze lag (eyes to the left of the ball).

<table>
<thead>
<tr>
<th>Elapsed time (milliseconds)</th>
<th>Horizontal gaze error (&quot;take&quot;)</th>
<th>Horizontal gaze error (&quot;swing&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>-0.84</td>
<td>-0.30</td>
</tr>
<tr>
<td>200</td>
<td>-1.12</td>
<td>-0.44</td>
</tr>
<tr>
<td>250</td>
<td>-1.36</td>
<td>-0.48</td>
</tr>
<tr>
<td>300</td>
<td>-1.92</td>
<td>-1.72</td>
</tr>
<tr>
<td>350</td>
<td>-2.17</td>
<td>-2.67</td>
</tr>
<tr>
<td>400</td>
<td>0.03</td>
<td>-0.28</td>
</tr>
<tr>
<td>450</td>
<td>10.90</td>
<td>7.02</td>
</tr>
<tr>
<td>500</td>
<td>6.37</td>
<td>-40.00</td>
</tr>
<tr>
<td>512</td>
<td>2.22</td>
<td>-60.75</td>
</tr>
</tbody>
</table>
3.4b: Vertical gaze position

The vertical tracking plot for Subject 1 is in Figure 15. Again, the line with the yellow triangles represents the target angle or the requisite gaze angle for our subject to foveate the tennis balls vertically. Notice the accuracy with which the subject tracks the balls in the vertical plane, in both the “take” and “swing” conditions. The most notable difference appears late in the pitch trajectory, as the subject continues to move his gaze substantially in a downward direction as the ball reaches the plate in the “take” condition, but discontinues the downward tracking trajectory at an elapsed time of about 0.45s in the “swing” condition.

Figure 15. Mean vertical gaze angle of Subject 1 with associated standard error bars.
Those vertical gaze tracking data for Subject 2 are shown in Figure 16. One can see that Subject 2 utilizes two slightly different strategies in the “take” and “swing” conditions. Similar to Subject 1, Subject 2 continues the downward gaze trajectory throughout the pitch in the “take” condition. However, in the “swing” condition Subject 2 shows a vertical gaze trajectory that places the gaze position below the ball for much of the ball’s trajectory. It is interesting to note, that, similar to the horizontal gaze error, Subject 1 and 2 have similar vertical gaze trajectories, but Subject 1 exhibits finer tracking accuracy with less variability (as demonstrated by the error bars).

Figure 16. Mean vertical gaze angle of Subject 2 with associated standard error bars.
Tables 8 and 9 below show the vertical gaze errors (as calculated from the mean gaze errors) for Subjects 1 and 2 in the “take” and “swing” conditions.

Table 8. Vertical gaze errors (degrees) in the "take" and "swing" conditions for Subject 1. Positive indicates that gaze is directed above the ball.

<table>
<thead>
<tr>
<th>Elapsed time (milliseconds)</th>
<th>Vertical gaze error (“take”)</th>
<th>Vertical gaze error (“swing”)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.77</td>
<td>-1.07</td>
</tr>
<tr>
<td>200</td>
<td>0.97</td>
<td>-1.82</td>
</tr>
<tr>
<td>250</td>
<td>1.05</td>
<td>-2.12</td>
</tr>
<tr>
<td>300</td>
<td>0.89</td>
<td>-1.73</td>
</tr>
<tr>
<td>350</td>
<td>0.37</td>
<td>-1.59</td>
</tr>
<tr>
<td>400</td>
<td>-0.23</td>
<td>-1.35</td>
</tr>
<tr>
<td>450</td>
<td>-4.56</td>
<td>-5.16</td>
</tr>
<tr>
<td>500</td>
<td>14.23</td>
<td>30.40</td>
</tr>
<tr>
<td>512</td>
<td>17.33</td>
<td>41.13</td>
</tr>
</tbody>
</table>

Table 9. Vertical gaze errors (degrees) in the "take" and "swing" conditions for Subject 2. Positive indicates that gaze is directed above the ball.

<table>
<thead>
<tr>
<th>Elapsed time (milliseconds)</th>
<th>Vertical gaze error (“take”)</th>
<th>Vertical gaze error (“swing”)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.66</td>
<td>-0.23</td>
</tr>
<tr>
<td>200</td>
<td>0.60</td>
<td>-0.63</td>
</tr>
<tr>
<td>250</td>
<td>0.73</td>
<td>-1.93</td>
</tr>
<tr>
<td>300</td>
<td>0.81</td>
<td>-3.54</td>
</tr>
<tr>
<td>350</td>
<td>0.73</td>
<td>-6.09</td>
</tr>
<tr>
<td>400</td>
<td>0.55</td>
<td>-5.53</td>
</tr>
<tr>
<td>450</td>
<td>6.36</td>
<td>-6.90</td>
</tr>
<tr>
<td>500</td>
<td>21.31</td>
<td>21.64</td>
</tr>
<tr>
<td>512</td>
<td>18.41</td>
<td>25.09</td>
</tr>
</tbody>
</table>
3.5: Success Rate

Table 10 contains the quality of contact observations for the pitches that were analyzed. Please refer to Table 3 for quality of contact grading criteria. From the 23 pitches that were analyzed for Subject 1 in the swing condition, 22 observations were made about the quality of contact. We were able to make quality of contact observations for all 13 pitches that were analyzed for Subject 2.

Table 10. Quality of the bat/ball contact for pitches that were analyzed.

<table>
<thead>
<tr>
<th></th>
<th>Solid Contact</th>
<th>Good Contact</th>
<th>Mild Contact</th>
<th>No Contact</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>14 (63.6%)</td>
<td>4 (18.2%)</td>
<td>4 (18.2%)</td>
<td>0</td>
<td>22</td>
</tr>
<tr>
<td>Subject 2</td>
<td>8 (61.5%)</td>
<td>1 (7.7%)</td>
<td>1 (7.7%)</td>
<td>3 (23%)</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 11 contains the quality of contact observations for all pitches that the subjects swung at. Of the 40 pitches Subject 1 swung at, 39 observations were made about the quality of contact. We were able to record observations on all 40 pitches that Subject 2 swung at.

Table 11. Quality of the bat/ball contact for all pitches swung at.

<table>
<thead>
<tr>
<th></th>
<th>Solid Contact</th>
<th>Good Contact</th>
<th>Mild Contact</th>
<th>No Contact</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>21 (53.8%)</td>
<td>7 (17.9%)</td>
<td>10 (25.6%)</td>
<td>1 (2.6%)</td>
<td>39</td>
</tr>
<tr>
<td>Subject 2</td>
<td>19 (47.5%)</td>
<td>9 (22.5%)</td>
<td>7 (17.5%)</td>
<td>5 (12.5%)</td>
<td>40</td>
</tr>
</tbody>
</table>

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Chapter 4: Discussion

4.1: Head Movements

Regarding the horizontal head movements generated by the subjects in this experiment (Figure 8), both subjects move the head substantially in the direction of the pitched ball in the “take” condition. This is largely in agreement with the conclusions of Hubbard and Seng\textsuperscript{12}, who stated that the head was rotated significantly when batters chose to take pitches but not when batters swung at pitches. On the other hand, the head movement in the “swing” condition varied rather significantly between the two subjects. Subject 1 demonstrated very little head movement throughout the pitch trajectory, while Subject 2 moved the head substantially in the direction of the ball.

Regarding the vertical head movements (Figure 9), again the two subjects demonstrated very similar mean head movement trajectories in the “take” condition, moving the head substantially downward. The vertical head movements were also similar between the two subjects in the “swing” condition. There was a substantial downward movement of the head later in the pitch trajectory. However, there was a moderate upward movement during the middle portions of the pitch trajectory (at about 0.35s after the pitch was released). This upward deflection most likely corresponds to the beginning of the swing (assuming that the swing time is approximately 194ms\textsuperscript{3}).
4.2: *Eye Movements*

Regarding the horizontal eye movements generated by the subjects in this experiment (Figure 11) in the “take” condition these mean data show that both subjects made a minimal leftward (opposite to the direction of the ball) eye movement followed by a large rightward movement. The leftward movement is most likely associated with the RVOR. On the other hand, in the “swing” condition for both subjects there is once again a leftward movement. A rightward movement then occurs late in the trajectory, but this late movement is very small. Overall, in the “swing” condition the eyes move very little, aligning similarly with the literature\textsuperscript{12}.

Regarding the vertical eye movements generated by the subjects in this experiment (Figure 12) in the “take” condition Subject 1 demonstrated a relatively significant downward movement while Subject 2 showed very little downward eye movement. On the other hand, in the “swing” condition both subjects demonstrated a downward movement. However, the downward movement was larger for Subject 2.

4.3: *Gaze Tracking Movements*

Those gaze tracking data from the two subjects are shown in Figures 13, 14, 15 and 16. There are several things that stand out when one examines these plots. First, the gaze tracking behaviors were similar between the two subjects. The only substantial difference in these plots is seen in the vertical gaze tracking plots in the “swing” condition. In this condition, the gaze position for Subject 1 is quite close to the ball
throughout much of the pitch trajectory. However, for Subject 2 the gaze position is substantially below the ball.

A second thing that is remarkable regarding these data is the difference in gaze tracking behavior between the “take” and “swing” conditions. Regarding the gaze tracking behavior in the horizontal direction, subjects track the ball in the “take” condition until an elapsed time of about 0.40s. At that elapsed time, subjects make large eye movements that place the gaze location at the plate. In this way, the subjects presumably hope to catch a brief glimpse of the ball as it crosses the plate. This behavior seems somewhat similar to the anticipatory saccades described for some non-expert subjects in the study of Bahill and LaRitz.

In the “swing” condition, subjects tended to maintain the horizontal gaze location relatively close to the ball location until late in the pitch trajectory. Late in the pitch trajectory the gaze remained in a relatively constant (rightward) location, presumably because subjects had finished or were about to finish their swing.

The difference in horizontal gaze tracking behavior opens the possibility that the differences in gaze tracking strategy between experts and novices as reported by Bahill and LaRitz may be at least partially attributable to differences in subjects’ expectations about the purposes of the experiment. Some subjects may have behaved as if they were “taking” a pitch, while other subjects may have behaved as if they were swinging at the pitch. In future studies of gaze tracking in baseball, it will be important to give subjects a specific set of instructions (eg. “keep your eye on the ball” or “swing at the ball”).
A third thing that these gaze tracking data demonstrate is that subjects did attempt to, and largely succeeded in, tracking the ball horizontally throughout much of the pitch trajectory. As discussed in the introduction, this could mean a number of things. It may be that tracking the ball through much of the pitch trajectory ensures that subjects maintain fixation early in the pitch trajectory in order to accurately assess cues to pitch trajectory such as ball rotation and change in angular ball size. This gaze tracking strategy could indicate that the swing is ballistic, and information can be gathered throughout the pitch trajectory and then used to improve batting in the future. Or finally, it could simply be that gaze tracking is a portion of an overall swing timing mechanism that involves such things as gaze movements and the swing stride.

A final thing of interest associated with the gaze tracking data has to do with the vertical gaze tracking data. Both subjects tended to maintain gaze close to the ball in the “take” condition, although there was no attempt late in the pitch trajectory to lower the eyes to the vertical location that the ball occupied at the plate. Thus, the vertical “take” data differed from the “horizontal” take data in that regard. The “swing” data on the other hand did vary between subjects. Subject 1 exhibited similar “take” and “swing” vertical gaze data. This subject kept his vertical gaze close to the ball in the “swing” condition, just as he had done in the horizontal meridian.

However, Subject 2 moved his eyes in such a way that his vertical gaze location was substantially below the ball until late in the pitch trajectory. The reasons behind this behavior are unclear, but the fact that this subject was able to maintain his gaze location on or near the ball in the “take” condition suggests that his vertical gaze tracking
behavior in the “swing” condition is not the result of poor estimation of the vertical target trajectory. Instead, a potential explanation for this behavior is poor cancellation of the vertical RVOR. This idea is arrived at by noting that fluctuations in the vertical eye position and fluctuations in the vertical head position occur at similar elapsed times. The author could not find any reports where vertical tracking and its importance to successful batting was specifically addressed in the literature. Some authors have proposed mechanisms for which vertical projections about pitch location are made, but none of these studies appeared to collect vertical eye and head movement data or comment on its relevance. Our data, although representing a small sample, indicates that tracking the vertical drop of the ball may not be as insignificant as previously thought.

It may be of no coincidence that Subject 1 made contact with 100% (97.4% of total swings) of the analyzed pitches he swung at, compared to 76% (87.5% of total swings) for Subject 2. The fact that Subject 1 had less variability in his head and eye movements and was also more successful at making contact, could be a strong indicator that accurate and consistent tracking is an important mechanism for making contact. This philosophy would correlate with Matsumiya and Kaneko’s findings that accurate pursuit eye movements are used to improve TTC estimation. Even more intriguing is the fact that Subject 1 appeared to rely more on his eyes than head under the swing condition. The decreased head movement is of note considering most hitting instructors teach young players to minimize head movements during the swing.

Our data and others lead us to wonder if it is possible to train someone to be a “super tracker”. Were our subjects born with an above average visual tracking system?
Or did they develop this system secondary to practice, creating the tools necessary to play collegiate level baseball. These questions again lead to the inherent difficulty of doing sports research. How do you as a researcher create an environment that is comparable to the environment experienced in sport? It would be ideal to monitor a player’s eye and head movements in actual game situations to determine what exactly is going on and try to correlate it with achieved success or failure. This utopia is unrealistic, even if mechanically possible it would be difficult to get human subjects research board approval to privy subjects to such uncontrolled conditions.

It would also be difficult to design a study that effectively correlates measured improvement in gaze with improvement or decline in hitting success. Over the time of the study did the subjects improve their biomechanics? Have they expanded their baseball intelligence? Did they deal with other psychological factors that could improve their ability to focus in stressful situations? All of these variables can affect the results in some way and it would be profoundly difficult to control for all of them.

4.4: Limitations

Our study has some limitations. The most obvious is the fact that our subjects knew exactly what pitch was coming in both the “take” and “swing” conditions. Therefore it was possible that they were not using the typical tracking strategy/strategies that would be used under real time situations where go/no go decisions are made when the pitch is in the air. Of course, batters generally must make up their minds as to whether they will swing or take a pitch relatively early in the pitch trajectory. Thus, the gaze
tracking behavior in our study is unlikely to vary too much from that when the pitch trajectory is less predictable.

Likewise, the subjects knew they would be swinging at all of the pitches. This knowledge could have altered their usual in-pitch information collection and data processing since a decision had already been made to initiate and complete the swing.

Our pitching machine threw pitches at a relatively low velocity. At higher pitch velocities, subjects may not have successfully tracked the pitch through as much of the pitch trajectory. Furthermore, if the spatial or temporal properties of the pitches had been less predictable, then this may have influenced the overall accuracy of gaze tracking. Finally, although this seems unlikely, less predictable pitches may have led subjects to make more anticipatory saccades.

4.5: Conclusion

The results from this study lend a few important observations to the literature regarding baseball tracking strategy. It is apparent that our subjects utilized different tracking strategies when swinging and taking. Thus, gaze tracking behaviors when batters do not swing at pitches may not apply when these same batters swing at pitches.

Importantly, our subjects used similar tracking strategies. The significance of this could be downplayed considering our small sample size, but the fact that both players competed at the collegiate level should be considered when evaluating their respective similarities in gaze positioning.

Most importantly, our data indicate that tracking in both the horizontal and vertical directions is an active and important aspect of successful hitting. Whether
tracking deep into the pitch trajectory is used to collect visual information for swing alteration, or serves as a timing mechanism to improve TTC, is up for debate.

Commercial devices, such as the one used in our study, may provide the means to improve tracking behavior of baseball players. Whether they are more effective at training appropriate tracking strategy than traditional batting practice is controversial, and is not the goal of this paper. Future analysis of experienced baseball players’ ocular tracking strategies could further expose the relative importance of accurate gaze positioning and its relationship to hitting success. Until then, we will focus on the facts; our subjects tracked over 90% of the pitch trajectory while attempting to make contact in situations where they knew with good reliability where the balls were going to end up. If accurate tracking were not important, then why, in a condition that almost every variable can safely be assumed, do our subjects still find it necessary to track?
References


Appendix A: Accuracy of ISCAN Eye Tracker

The assessment of the accuracy of the ISCAN eye tracker was previously described by Nathan Atterholt in his 2011 Master of Science thesis at the Ohio State University. It will only briefly be described here. The subject wore both a search coil (the gold standard eye tracker) on the left (lead) eye and the ISCAN video eye-tracker. The subject stood within a magnetic field coil cage (Remmel Labs) placed 39 feet 7 inches from the pitching machine used throughout the experiment. The subject then attempted to partially or fully track pitches thrown by the pitching machine with the eyes while the head was kept as still as possible. Analog signals from both the search coil and the ISCAN video-tracker (left eye) were recorded simultaneously at 2000Hz for 14 pitches. The eye movement amplitudes (as determined from the search coil) ranged from 21.6 deg to 47.2 deg (mean = 33.4deg ± 7.7deg). The eye movement typically consisted of a rapid movement followed by a slower drifting movement.

The eye movement traces for each pitch from the two devices were similar, but the ISCAN clearly had a temporal delay compared to the search coil. This delay was similar from pitch to pitch. The ISCAN data were “corrected” for this delay, and then the angular values from the eye trackers were each adjusted if necessary such that the beginning of each data set was zero degrees. After that the difference in ISCAN and coil positions was determined for all pitches. Differences were determined every 0.0005s. This resulted in 18,800 comparisons. The mean difference in position between the two eye trackers was – 0.13 deg (the minus sign indicates that the ISCAN lagged behind the search coil). The standard deviation of this mean was 1.35 deg.
Appendix B: Accuracy of Flock of Birds Horizontal Rotation Measurements

The accuracy of the horizontal rotational values from the Flock of Birds head tracker was assessed in the following way. The Flock of Birds head tracker could not be compared directly to measurements from the magnetic search coil because noise was introduced into the Flock of Birds recordings by the magnetic field of the search coil system. Therefore, the same device as that used to assess the temporal latency of the Microstrain was used (Figure 6).

A protractor was mounted on a vertical rod. The Flock of Birds receiver was rigidly mounted on a piece of plastic attached to the protractor. Finally, a laser was mounted above the Flock of Birds receiver. Thus, the protractor, the Flock of Birds receiver, and the laser could all be rotated together about the vertical rod (which was placed through a hole drilled through a table) on the bottom of the apparatus.

On the table upon which the protractor/Flock of Birds receiver/laser apparatus was placed, two photodiodes were mounted such that when the laser was rotated to the appropriate angle, the laser beam would strike the photodiodes. To determine the angle between the photodiodes, the following procedure was followed. The protractor/Flock of Birds receiver/laser apparatus was rotated such that a change in the voltage from the left photodiode was detected. At that time, the angle through which this apparatus was rotated was measured from the protractor and from the Flock of Birds receiver. This measurement procedure was repeated for the right photodiode.
The angle between the two photodiodes as measured with the protractor (which could be read to within about 0.50deg) was compared to the same angle as measured with the Flock of Birds receiver. The angles for the protractor and Flock of Birds receiver were within 20 arc minutes of one another on one occasion and within 6 arc minutes on another occasion. This confirmed the static accuracy of the Flock of Birds receiver. The angle between the two photodiodes as measured with the Flock of Birds was 79.7deg.

Next, the protractor/Flock of Birds receiver/laser apparatus was rotated rapidly by hand from left to right 30 times. The laser struck each photodiode during this rotation. Voltages were recorded from each photodiode (through a 12-bit analog to digital converter, CIO-DAS08, Measurement Computing, Norton, MA) at 1000Hz. Data were simultaneously recorded from the Flock of Birds receiver. All of these data recordings were made using the same recording program as that used in the main experiment. Those data from the analog to digital converter and those from the Flock of Birds were then synchronized using a custom computer program.

The synchronized data were then used to determine the times at which the laser struck the left photodiode and the times when the laser struck the right photodiode. These times were compared to the times when the horizontal angle reported by the Flock of Birds was as close as possible to the rotational values expected from the Flock of Birds (as determined from the earlier static comparison to the protractor) when the laser struck the photodiodes. The Flock of Birds was found to have a temporal delay. The mean delay for the Flock of Birds as determined from 30 measurements from the left photodiode was within 2.1ms of the mean delay as determined from 30 measurements from the right
photodiode. The delays from the left and right photodiodes were all combined and a final mean delay was determined for the Flock of Birds.

Those data from the Flock of Birds were then corrected for this mean delay, Finally, the angular values as measured from the Flock of Birds (corrected for the temporal delay) when the laser struck each photodiode were compared to the expected angular values from the Flock of Birds (as determined from the static calibration procedure). The mean difference between the measured and expected values for 60 comparisons was -0.18deg. The negative mean value indicates that the corrected values from the Flock of Birds were less than the expected values. The standard deviation of this mean was 0.97deg.
Appendix C: Horizontal Target Angle Calculation

The following calculations were used to determine the horizontal angle of the ball relative to the batter at our elapsed times of interest. These values represent the change in horizontal gaze angle required for the batter to accurately fixate the pitched ball.

Referring to Figure 17 below, $\alpha$ is the horizontal angle of the ball, while $X$ is the distance of the subject from the pitching machine (56.3 feet), $R$ is the distance the ball has traveled at the elapsed time of interest, and $y$ is the anterior-posterior (direction relative to the subject) distance of the subject from the plate.

$$ P = X - R $$ (1)

$$ \tan \gamma = \frac{P}{y} $$ (2)

$$ \alpha = 90 - (\gamma + \beta) $$ (3)

Figure 17. Diagram for horizontal target angle determination.
Appendix D: Vertical Target Angle Calculation

The following calculations were used to determine the vertical angle of the ball in relation to the batter at our elapsed times of interest. These values represent the change in vertical gaze angle required for the batter to accurately fixate the pitched ball.

Referring to Figure 18, $P$ is the linear distance from the plate to the ball, $y$ is the anterior-posterior (direction relative to the subject) distance of the subject from the plate, and $\gamma$ is the vertical angle of the ball.

\[
\tan \theta = \frac{P}{y} \\
\sin \theta = \frac{P}{z} \\
\tan \gamma = \frac{x}{z}
\]

Figure 18. Diagram for vertical target angle determination.
Appendix E: Correction of Horizontal Gaze Angle for Horizontal Translation

The following calculations were performed to correct the horizontal gaze angle for horizontal translation. For example, if the head is translated toward the plate, then the gaze is shifted in the direction of the plate. However, the resultant gaze shift is not accounted by our rotational measurements of the eye and head.

Referring to Figure 19, \( z \) is the distance from the plate to the pitching machine, \( y \) is the distance from the batter to the plate, \( T \) is the amplitude of the translation, \( \alpha \) is the original gaze angle (prior to correction for translation), and \( \alpha_{\text{corrected}} \) is the gaze angle corrected for translation. The influence of translation was only added if the effect resulted in a correction of greater than 0.50\( \text{deg} \), and if the gaze was directed to the right of straight ahead.

\[
\tan \delta = \frac{y}{z} \tag{4}
\]
\[
90 - (\delta + \alpha) = \beta \tag{5}
\]
\[
\tan \beta = \frac{R}{y} \tag{6}
\]
\[
R - T = S \tag{7}
\]
\[
\tan \varepsilon = \frac{S}{y} \tag{8}
\]
\[
\kappa = \beta - \varepsilon \tag{9}
\]
\[
\alpha_{\text{corrected}} = \alpha + \kappa \tag{10}
\]
Figure 19. Diagram for horizontal gaze angle determination, corrected for translation.
Appendix F: Correction of Vertical Gaze Angle for Vertical Translation

The following calculations were performed to correct the vertical gaze angle for vertical translation. For example, if the head is translated down, then the vertical gaze is shifted in a downward direction. However, the resultant gaze shift is not accounted by our rotational measurements of the eye and head.

Referring to Figure 20, $x$ is the distance of the ball from the batter, $P$ is the linear drop of the ball at the distance $x$, $T$ is the vertical translation, $\alpha_v$ is the vertical gaze angle prior to correction for translation, and $\alpha_v\text{corrected}$ is the vertical gaze angle after correction for translation. The influence of translation was only added if the effect resulted in a correction of greater than 0.50deg, and if the gaze was directed to the right of straight ahead.

\[
\sin \beta = \frac{y}{x} \tag{13}
\]

\[
\tan \alpha_v = \frac{r_v}{x} \tag{14}
\]

\[
P = (r_v - T) \tag{15}
\]

\[
\tan \alpha_v\text{corrected} = \frac{P}{x} \tag{16}
\]
Figure 20. Diagram for vertical gaze angle determination, corrected for translation.
Appendix G: Cross-talk Due to Head Tilt

Artifacts can be induced in the horizontal and vertical eye movement measurements when the head is tilted toward the shoulder. For example, if the head is tilted toward the right shoulder and then the eyes are rotated to the right (as measured with the eyetracker), then relative to the outside world ("space") the eyes are effectively moving down and right (Figure 21). This vertical motion would not be detected by the eyetracker, because the eyetracker measures motion relative to the head (since the eyetracker is attached to the head).

On the other hand, if for example the head is tilted to the right shoulder and the eyes are rotated downward, then relative to space the eyes are being rotated down and left. Once again, the horizontal motion would not be detected by the eyetracker. We calculated the potential influence of these artifacts on the eye movement measurements. The results are shown in Tables 12 and 13 below. These effects are relatively small, and the largest effects generally occur at or near the time the ball reaches the plate. Since these effects do not change the study conclusions, they were not incorporated into the final gaze calculations presented in the paper.
Table 12. Mean degrees of change in vertical eye rotation associated with horizontal eye rotation and head tilt (negative is down).

<table>
<thead>
<tr>
<th>Elapsed time (milliseconds)</th>
<th>Subject 1 Take Swing</th>
<th>Subject 1 Swing</th>
<th>Subject 2 Take Swing</th>
<th>Subject 2 Swing</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.00±0.00</td>
<td>0.02±0.02</td>
<td>0.00±0.01</td>
<td>-0.01±0.03</td>
</tr>
<tr>
<td>200</td>
<td>0.00±0.01</td>
<td>0.07±0.04</td>
<td>-0.01±0.01</td>
<td>-0.01±0.05</td>
</tr>
<tr>
<td>250</td>
<td>0.01±0.03</td>
<td>0.16±0.09</td>
<td>-0.01±0.02</td>
<td>0.03±0.06</td>
</tr>
<tr>
<td>300</td>
<td>0.05±0.06</td>
<td>0.28±0.16</td>
<td>-0.03±0.05</td>
<td>0.13±0.10</td>
</tr>
<tr>
<td>350</td>
<td>0.14±0.13</td>
<td>0.44±0.22</td>
<td>-0.03±0.09</td>
<td>0.50±0.31</td>
</tr>
<tr>
<td>400</td>
<td>-0.23±0.41</td>
<td>0.14±0.22</td>
<td>-0.04±0.14</td>
<td>0.91±0.34</td>
</tr>
<tr>
<td>450</td>
<td>-1.91±0.80</td>
<td>-1.36±0.52</td>
<td>-0.98±0.96</td>
<td>0.17±0.67</td>
</tr>
<tr>
<td>500</td>
<td>-2.74±0.83</td>
<td>-2.36±0.91</td>
<td>-1.51±1.34</td>
<td>0.60±0.96</td>
</tr>
<tr>
<td>512</td>
<td>-2.65±0.82</td>
<td>-2.41±0.97</td>
<td>-0.63±2.45</td>
<td>0.84±0.83</td>
</tr>
</tbody>
</table>
Table 13. Mean degrees of change in horizontal eye rotation associated with vertical eye rotation and head tilt (negative is left).

<table>
<thead>
<tr>
<th>Elapsed time (milliseconds)</th>
<th>Subject 1 Take Swing</th>
<th>Subject 1 Swing</th>
<th>Subject 2 Take Swing</th>
<th>Subject 2 Swing</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.00±0.00</td>
<td>0.00±0.01</td>
<td>-0.01±0.01</td>
<td>0.01±0.04</td>
</tr>
<tr>
<td>200</td>
<td>0.00±0.00</td>
<td>-0.01±0.02</td>
<td>0.01±0.01</td>
<td>0.00±0.07</td>
</tr>
<tr>
<td>250</td>
<td>0.00±0.00</td>
<td>-0.06±0.05</td>
<td>0.02±0.03</td>
<td>-0.08±0.15</td>
</tr>
<tr>
<td>300</td>
<td>0.00±0.00</td>
<td>-0.19±0.10</td>
<td>0.03±0.04</td>
<td>-0.41±0.37</td>
</tr>
<tr>
<td>350</td>
<td>-0.01±0.01</td>
<td>-0.30±0.16</td>
<td>0.03±0.04</td>
<td>-1.13±0.62</td>
</tr>
<tr>
<td>400</td>
<td>0.02±0.04</td>
<td>-0.26±0.23</td>
<td>-0.04±0.11</td>
<td>-1.19±0.71</td>
</tr>
<tr>
<td>450</td>
<td>0.18±0.10</td>
<td>-1.10±0.52</td>
<td>-0.01±0.20</td>
<td>-2.06±0.97</td>
</tr>
<tr>
<td>500</td>
<td>0.23±0.12</td>
<td>-0.42±1.07</td>
<td>-0.09±0.22</td>
<td>-0.88±0.92</td>
</tr>
<tr>
<td>512</td>
<td>0.20±0.11</td>
<td>0.32±1.05</td>
<td>-0.07±0.28</td>
<td>-0.61±1.11</td>
</tr>
</tbody>
</table>

Figure 21. Diagram of cross-talk induced by head tilt.