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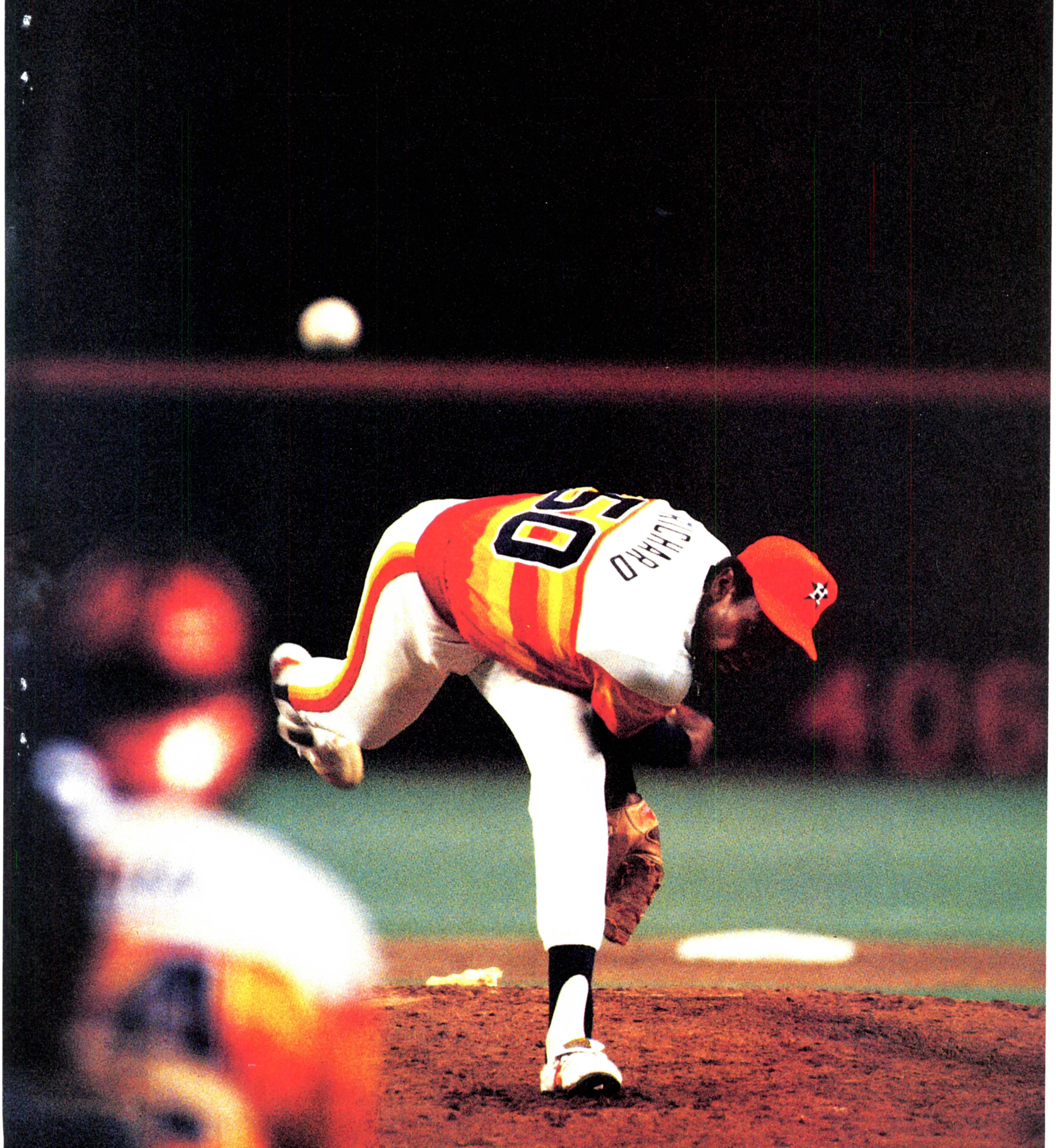

Why Can't Batters Keep Their Eyes on the Ball?

A laboratory study of batters tracking a fastball shows the limitations of some hoary baseball axioms

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Ted Williams, arguably the best hitter in the history of baseball, has described hitting a baseball as the most difficult single act in all of sports (Williams and Underwood 1982). The velocity of the ball approaches 100 mph, producing angular velocities greater than 500°/sec as the ball passes the batter. Humans cannot track targets moving faster than 70°/sec (Schalen 1980); yet, professional batters manage to hit the ball with force consistently and are able to "get a piece of the ball" in an average of more than 80% of their batting attempts. In this paper we investigate how they do this by examining a professional athlete tracking a pitched ball, and we demonstrate the superiority of his eye movements and head-eye coordination to those of our other subjects.

Why did we want to study a batter tracking a baseball? We wanted to learn more about how the brain controls movement, and we therefore were searching for a situation in which a human was performing optimally. This condition is fulfilled by a professional baseball player hitting a baseball.

We studied our batters' use of the four basic types of eye movements. These are: saccadic eye movements, which are used in reading text or scanning a roomful of people; vestibulo-ocular eye movements, used to maintain fixation during head movements; vergence eye movements, used when looking between near and far objects; and smooth-pursuit eye movements, used when tracking a moving object. These four types of eye movements have four independent control systems, involving different areas of the brain. Their dynamic properties, such as latency, speed, and high-frequency cutoff values, are different, and they are affected differently by fatigue, drugs, and disease.

The specific actions of the four systems can be illustrated by the example of a duck hunter sitting in a rowboat on a lake. He scans the sky using saccadic eye movements, jerking his eyes quickly from one fixation point to the next. When he spots a duck, he tracks it using smooth-pursuit eye movements. If the duck comes very close to him, he tracks it by moving his eyes toward each other with vergence eye movements. Throughout all this, he uses vestibulo-ocular eye movements to compensate for the movement of his head caused by the rocking of the boat. Thus, all four systems are continually used to move the eyes.

Figure 1. A fastball is simulated when this plastic ball is pulled along the fishing line by the string, which is connected to a motor. The infrared emitters and photodetectors that monitor the eye movements of a subject trying to track this fastball are mounted on the special eyeglasses shown here worn by Dr. Bahill. Two light-emitting diodes used to monitor head movements sit directly on top of the head, and the third is at the end of the stalk.

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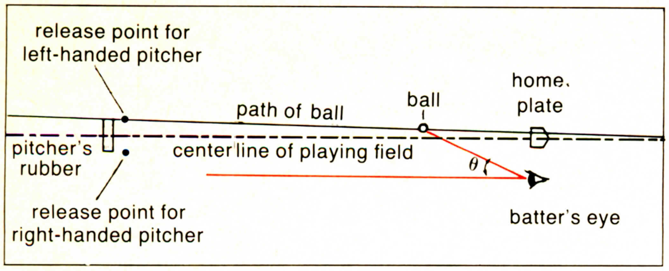

Figure 2. The horizontal angle of the ball, θ, as defined in this study, ranges from near 0° when the pitcher releases the ball to 90° when the ball crosses the plate.

The batter has the potential to use the head-movement system in addition to each of these eye-movement systems. Does he? Earlier studies have suggested several strategies for tracking a baseball: track the ball with head movements and smooth-pursuit eye movements and fall behind in the last 5 ft of flight; track with eyes only, or with head only, and fall behind in the last 5 ft; track the ball over the first part of its trajectory with smooth-pursuit eye movements, make a saccadic eye movement to a predicted point ahead of the ball, continue to follow it with peripheral vision, and finally, at the end of the ball's flight, resume smooth-pursuit tracking with the ball's image on the fovea, the small area in the center of the retina that has fine acuity (Hubbard and Seng 1954;

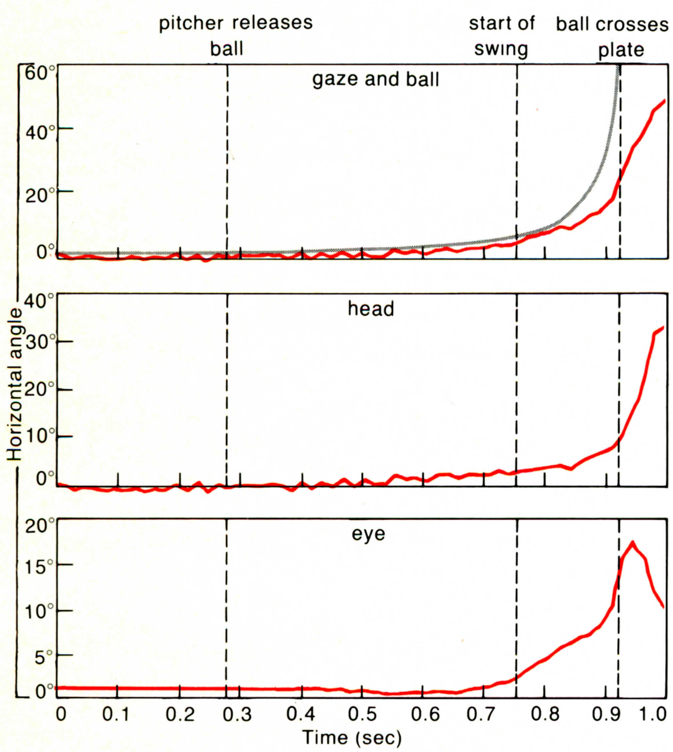

Figure 3. The gray line in the top graph represents the horizontal angle of a simulated 70-mph fastball as it would be seen by a right-handed batter facing a left-handed pitcher if the batter were able to track the ball perfectly. The colored line represents the actual horizontal angle of gaze of the subject, a graduate student, trying to track this ball; this curve is generated by combining horizontal head angle (*middle graph*) and horizontal eye angle (*bottom graph*), the two parameters monitored in our simulation. Movements to the right appear as upward deflections. The start of the swing was estimated from Hubbard and Seng (1954).

Bahill et al. 1981; LaRitz et al. 1983; Bahill and LaRitz 1983). We will examine each of these strategies.

The simulated fastball

To discover how well a batter tracked the ball, we had to be able to determine the position of the ball at all times, and thus we could not use a real pitcher or a throwing machine. Instead, we simulated the trajectory of a pitched baseball, as shown in Figure 1. We threaded a fishing line through a white plastic ball and stretched the line between two supports, which were set 80 ft apart in order to accommodate the 60.5 ft between the pitcher's rubber and home plate; a string was attached to the ball and wrapped around a pulley attached to a motor, so that when the motor was turned on, the string pulled the ball down the line at speeds between 60 and 100 mph. (Baseball is a game of inches, so we have not converted our distances or velocities to metric units.) The ball crossed the plate 2.5 ft away from the subject's shoulders, simulating a high-and-outside fastball thrown by a left-handed pitcher to a right-handed batter. This, like all our constraints, was designed to give our subjects the best possible chance of keeping their eyes on the ball. A low curve ball thrown by a right-handed pitcher would have been much harder to track.

By controlling the speed of the motor and counting the rotations of the shaft, we could compute the position of the ball at every instant of time, and thus compare the position of the ball to the position of the batter's gaze. We define both positions in terms of the horizontal angle of the ball: the angle between the line of sight from the batter's eye pointing straight out toward center field and the line of sight pointing at the ball (see Fig. 2). This angle is slightly more than 0° when the pitcher releases the ball, and it increases to 90° when the ball crosses the plate.

We monitored horizontal eye movements with a photoelectric system using infrared emitters and photodetectors aimed at the iris-sclera borders of both eyes (Bahill 1981). As the eye moves horizontally, the amount of reflected infrared light changes, causing a variation in the current of the photodetectors. Amplifying the difference in the currents of the two detectors produces a voltage proportional to horizontal eye position. (Although we sampled each millisecond, our data were filtered and compressed, producing 30-Hz position traces and 7-Hz velocity traces.) Since we deliberately configured the simulation to minimize vertical target movements, vertical eye movements, which were measured by electro-oculography, were negligibly small (LaRitz et al. 1983).

Head movements were monitored with a video camera mounted on the ceiling, looking down on the subject's head. Two light-emitting diodes (LEDs) were placed on top of the subject's head, and a third LED was mounted on a stalk 7.8 in. above the head. The video signal was digitized, and the coordinates of the centers of the three LEDs were computed; from these coordinates we could compute the yaw, pitch, and roll angles, as well as the lateral and forward-backward positions of the head.

We ran several subjects through our simulation, including graduate students, students on the Carnegie-Mellon University baseball team, and Brian Harper, a member of the Pittsburgh Pirates; all had 20/20 uncorrected vision. Figure 3 shows the data of one simulation, which were typical of the results obtained with students. This subject tracked the ball well (<2° error) until the ball reached 16°, corresponding to 9 ft in front of the plate, at which point he started to fall behind. When the ball reached the 50° point, 2 ft in front of the plate, the image of the ball was 34° off his fovea. The ball covered the angle between 16° and 50° in 67 msec, for an average angular velocity of 507°/sec—much too fast for humans to track. The maximum smooth-pursuit velocity occurred just before the ball crossed the plate: the eye was going 50°/sec, and the head was going 20°/sec, giving a gaze velocity of 70°/sec. This subject used both head and eye movements to track the ball; in contrast, some of our student subjects used only eye movements to track the ball, and others primarily used head movements. After the ball crossed the plate, this subject made a large head movement and a saccadic eye movement.

Figure 4 shows an example of the results produced by the professional ballplayer, Brian Harper. He tracked the ball using head and eye movements, keeping his eye on the ball longer than our other subjects did. He was able to keep his position error below 2° until the ball reached 24°, 5.5 ft from the plate. At the 50° point, the image of the ball, which was traveling at 1,100°/sec, was 16° off his fovea—better than our other subjects, but too far off to track the ball. The peak velocity of his smooth-pursuit tracking was 120°/sec; at this point his head velocity was 30°/sec, thus producing a gaze velocity of 150°/sec. In three simulated pitches to the professional athlete, at speeds of 60, 67, and 70 mph, the overall tracking patterns were the same; his maximum smooth-pursuit eye velocities were 120, 130, and 120°/sec respectively. (One detail, the small saccade at 0.3 sec in Figure 4, does not appear in the other pitches, but it is, we think, insignificant.)

The gaze graph of the professional athlete differs from the one in Figure 3 in that, in addition to combining eye angle and head angle, it also takes into account the side-to-side and front-to-back movements of the head; such translations of the head can produce changes in the gaze angle (McDonald et al. 1983). The data show that the contribution of the translation angle was slight until the ball was almost over the plate.

We found that our professional athlete was able to repeat his stance consistently. At the beginning of the pitch, his head position was the same (within 1°) for each of the three simulated pitches we recorded. When he was looking at the ball in the beginning of the simulation, his eyes were rotated 22° to the left; his head was rotated left 65° (yaw) and was tilted down 23° (pitch) and right 12° (roll). While tracking the ball, as shown in Figure 4, the eye angle changed by 17° and the yaw angle changed by 13°; the pitch and roll angles changed by less than 2°.

Obviously, the professional athlete had faster smooth-pursuit eye movements than our other subjects. In fact, he had faster smooth-pursuit eye movements than any reported in the literature. He also had better head-eye coordination, tracking the ball with equal-sized head and eye movements, whereas the other subjects usually had disproportionately large head or eye movements.

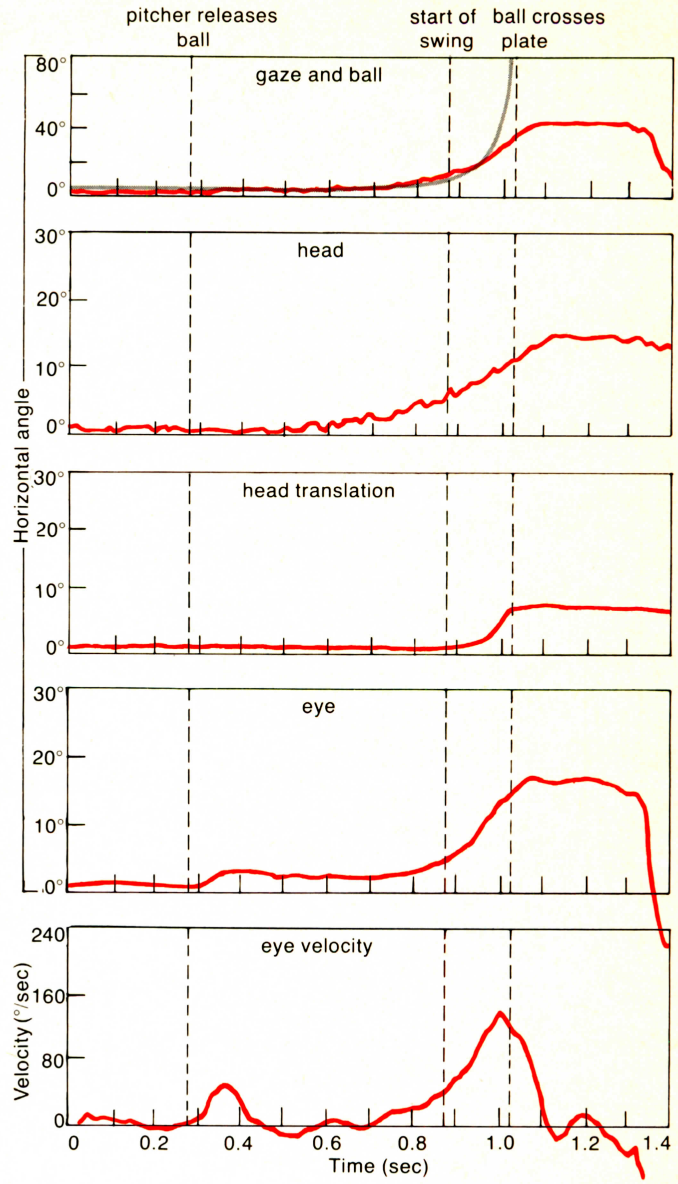

Figure 4. The success of a professional baseball player in tracking a simulated 60-mph fastball is shown in these graphs, which have the same format as in Figure 3, except that the horizontal-gaze angle also takes into account the head-translation angle shown in the middle graph, which represents the eye movement necessary to compensate for side-to-side and front-to-back movement of the head.

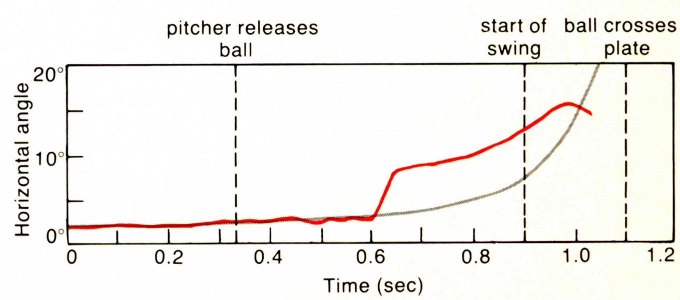

Figure 5. This subject was able to see the ball hit his bat by making an anticipatory saccade, indicated by the jump in the gaze angle (*colored line*). The saccade put his eye ahead of the ball (*gray line*), which he continued to track with peripheral vision — as evidenced by the gaze and ball curves running parallel — until the ball was on the fovea at the point of contact. The subject did not move his head until after the ball crossed the plate.

The science of batting

We should caution that our study, although it does warrant some useful generalizations, has limitations. First, our data pool is small; these experiments were difficult to perform, and from our 50 hours of experimentation we have complete head and eye data for 6 simulated pitches, and partial data for another 15. Second, our subjects never actually swung the bat at the ball; it is possible that head-eye coordination would be different if the subjects did swing at the ball. Third, we simulated the easiest pitch for a batter to track: a high-and-outside fastball thrown by an opposite-handed pitcher, in this case a left-handed pitcher to a right-handed batter. Nevertheless, even with these limitations, we can reasonably make the following generalizations.

Although the professional athlete was better than the students at tracking the simulated fastball, it is clear from our simulations that batters, even professional batters, cannot keep their eyes on the ball. Our professional athlete was able to track the ball until it was 5.5 ft in front of the plate. This could hardly be improved on; we hypothesize that the best imaginable athlete could not track the ball closer than 5 ft from the plate, at which point it is moving three times faster than the fastest human could track. This finding runs contrary to one of the most often repeated axioms of batting instructors—"Keep your eye on the ball"—and makes it difficult to account for the widely reported claim that Ted Williams could sometimes see the ball hit his bat.

If Ted Williams were indeed able to do this, it could only be possible if he made an anticipatory saccade that put his eye ahead of the ball and then let the ball catch up to his eye. This was the strategy employed by the subject of Figure 5: this batter observed the ball over the first half of its trajectory, predicted where it would be when it crossed the plate, and then made an anticipatory saccade that put his eye ahead of the ball. Using this strategy, the batter could see the ball hit the bat.

But why would a batter want to see the ball hit his bat? He could not, because of his slow reaction time, use the information gained in the last portion of the ball's flight to alter the course of the bat. We suggest that he uses the information to discover the ball's actual trajectory; that is, he uses it to learn how to predict the ball's location when it crosses the plate—how to be a better hitter in the future. The anticipatory saccade must be made before the end of the trajectory, because saccadic suppression prevents us from seeing during saccades (Stark et al. 1969; Matin 1982). This suppression of vision extends about 20 msec after the saccade. So if you want to see the ball hit the bat, you must make your anticipatory saccade early in the trajectory.

The vestibulo-ocular system is little used when tracking a baseball. However, in monitoring the eyes of the professional ballplayer, we did detect a small vestibulo-ocular movement to the left during the early part of the ball's trajectory, as the head was moving to the right; this appears as the slight dip between 0.5 and 0.7 in the eye trace in Figure 4. At this point the head position was changing faster than the angular position of the ball, and the vestibulo-ocular eye movement compensated for the premature head movement. Why would the batter want to give his head a head-start? The answer is that the head is heavier than the eye and consequently takes longer to get moving; therefore, in the beginning of the movement, as the head starts turning to the right ahead of the ball, the vestibular system in the inner ear signals the ocular system to make a compensating eye movement.

However, this vestibulo-ocular compensation must soon stop. In the end, the eye and the head must both be moving to the right, and the batter must therefore suppress his vestibulo-ocular reflex so that the tracking head movement does not produce compensating eye movements that would take his eye off the ball. The professional athlete was very good at suppressing his vestibulo-ocular reflex. Some of our student subjects did not make head movements until after the ball crossed the plate; others moved their heads very little. Perhaps they did this because they could not suppress the vestibulo-ocular reflex very well.

Batters do not use vergence eye movements. This is reasonable, since vergence eye movements are not needed to track the ball between 60 and 6 ft from the plate, and since there is not sufficient time to make such movements between 6 ft and the point of contact. Indeed, our data indicated no vergence eye movements; so any claim that a batter actually saw the ball hit the bat must be based on monocular vision; only the dominant eye tracks the ball.

The fact that our professional athlete used his head to help track the ball seems to violate another often-repeated batting axiom, "Don't move your head." The professional made small tracking head movements in the range of 10° to 20°. He was able to suppress the vestibulo-ocular reflex for these movements, which were probably small enough to go unnoticed by a coach. However, body movements could produce head movements of 90° or more; it may be difficult to suppress the vestibulo-ocular reflex for these large body-induced movements, which along with correlated poor performance would be noticed by a coach. Therefore, we think the axiom should be expanded: "Don't let your body move your head, but it's okay to move your head to track the ball."

It is well known in baseball that right-handed batters have significantly greater success hitting against left-handed pitchers than against right-handed pitchers. The obverse is true for left-handed batters. This difference in most batters' ability is perplexing, since our computer analysis shows that for an overhand fastball the only difference is a 2° offset in the beginning; there is no difference in either angular position or angular velocity over the last fourth of the pitch. A fastball thrown by a right-handed pitcher to a right-handed batter would have started with an initial horizontal angle of +1° instead of +3°, perhaps making it harder to track the ball by forcing the eye into a more eccentric position; eye movements in more extreme positions of gaze are less accurate (Yee et al. 1983). However, we found the effect is small in this case. We suspect, with little evidence, that for a right-handed batter the right-handed pitcher is harder to hit than the left-handed pitcher only for the curve ball.

Our findings should generalize to other sports. In tennis, for example, the distances are similar, 60 ft for baseball and 78 ft for tennis, as are the linear velocities, 100 mph for a fast pitch and 110 mph for a fast serve.

There is often an abrupt change in the ball's trajectory just before the player hits it: the baseball breaks and the tennis ball bounces. Like batting instructors, tennis coaches teach beginners to use the strategy with the anticipatory saccade in order to see the ball hit the racket; this strategy is probably only useful as a learning tool. Therefore, we suggest that neither baseball players nor tennis players keep their eyes on the ball. The success of the good players is due to faster smooth-pursuit eye movements, a good ability to suppress the vestibulo-ocular reflex, and the occasional use of an anticipatory saccade.

Sometimes our subjects used the strategy of tracking with head and eyes and falling behind in the last 5 ft, and sometimes they used the strategy of tracking with head and eyes but also using an anticipatory saccade. It has been speculated (L. Matin, pers. com.) that athletes might use the latter strategy when they are learning the trajectory of a new pitch and the former strategy when hitting home runs.

References

Bahill, A. T. 1981. *Bioengineering: Biomedical, Medical and Clinical Engineering.* Prentice-Hall.

Bahill, A. T., et al. 1981. Does a baseball player "Keep his eye on the ball?" In *Modeling and Simulation: Proceedings of the 12th Annual Pittsburgh Conference*, ed. W. Vogt and M. Mickle, pp. 1201–06. Pittsburgh: Instrument Soc. Am.

Bahill, A. T., and T. LaRitz. 1983. Do baseball and cricket players keep their eyes on the ball? *Proceedings of the 1983 International Conference on Systems, Man and Cybernetics* (*India*), pp. 79–83. IEEE.

Hubbard, A. W., and C. N. Seng. 1954. Visual movements of batters. *Res. Quart.* 25:42–57.

LaRitz, T., D. J. Hall, and A. T. Bahill. 1983. Modeling head and eye coordination of baseball players. In *Modeling and Simulation: Proceedings of the 14th Annual Pittsburgh Conference*, ed. W. Vogt and M. Mickle, pp. 1059–63. Pittsburgh: Instrument Soc. Am.

Matin, E. 1982. Saccadic suppression and the dual mechanism theory of direction constancy. *Vision Res.* 22:335–36.

McDonald, J. D., A. T. Bahill, and M. B. Friedman. 1983. An adaptive control model for human head and eye movements while walking. *IEEE Transactions on Systems, Man, and Cybernetics* SMC-13:167–74.

Schalen, L. 1980. Quantification of tracking eye movements in normal subjects. *Acta. Otolaryngol.* 90:404–13.

Stark, L., J. A. Michael, and B. L. Zuber. 1969. Saccadic suppression: A product of the saccadic anticipatory signal. In *Attention in Neurophysiology*, ed. C. R. Evans and T. B. Mulholland, pp. 281–303. London: Butterworths.

Williams, T. S., and J. Underwood. 1982. *The Science of Hitting.* Simon and Schuster.

Yee, R. D., R. A. Goldberg, O. W. Jones, R. W. Baloh, and V. Honrubia. 1983. Effects of eccentric gaze on pursuit. *Invest. Ophthalmol. Vis. Sci.* 24:1108–14.

"Then, as you can see, we give them some multiple-choice tests."