10

The Rising Fastball and Other Perceptual Illusions of Batters

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10.1 INTRODUCTION

Sometimes athletes develop effective strategies although their underlying assumptions are fallacious. Baseball provides an example in which misunderstood physical and psychological phenomena are the basis of strategies of both the pitcher and the batter.

With limited knowledge of the physics of a pitch's trajectory, baseball players argue that a high, hard fastball will sometimes accelerate and rise suddenly as it approaches the plate. Batters claim the ball can jump a foot or more just before the pitch reaches the strike zone. The batter is unable to adjust to this apparent rapid change in trajectory, as the ball seems to hop over the bat.

This perceived rise occurs on fastballs that have exceptional speed, are belt high or higher, and, most often, are on the inside half of the strike zone. Batters say that the pitcher "pumped it up," or "put a little extra on that one." In describing Dwight Gooden, Tony Gwynn states, "He rears back and throws you that high-rising fastball whenever he needs a big pitch" (Gwynn and Rosenthal, 1992). The rising fastball is often referred to as "smoke," "cheese," or "express."

Pitchers have devised various means for producing and enhancing the rise effect. The pitch is thrown with an overhand or three-quarter delivery so that a rapid backspin is imparted to the ball (Seaver and Lowenfish, 1984). The ball is usually gripped with the index and middle fingers extending across four seams (House, 1994). Each seam is a ridge that provides high impedance to the airflow around the ball when the seam is perpendicular to the direction of flight. Backspin with four seams perpendicular to the trajectory is thought to give the ball maximum "lift." In general, pitchers believe that this lift accounts for the rise experienced by batters (e.g., see Seaver and Lowenfish, 1984, p. 99 and Flatow, 1988, p. 93). For a literature review of the rising fastball, see McBeath (1990).

A phenomenon that batters experience far more often than the rising fastball, however, is a pitch that appears to break sharply downward as it nears the plate. Several kinds of pitches behave in this way – the overhand or three-quarter curveball, the sinking fastball (thrown three-quarter or sidearm, with strong pressure applied by the index finger), the split-finger fastball or forkball (thrown directly overhand), and several kinds of change ups. We will refer to these pitches collectively as "breaking pitches." A breaking pitch will be defined as any pitch that seems to exhibit an abrupt drop near the plate.

Batters describe these pitches with phrases such as, "the bottom dropped out of it" or "it fell off the table." Gwynn uses the metaphor, "a dead fish." He writes that hitting a sinker is "like hitting a rock – it won't go anywhere" (Gwynn and Rosenthal, 1992).

Breaking pitches should be thrown very low in the strike zone or even a little below the knees. If the batter makes contact with such a pitch, he is most likely to hit the ball on the ground. The objective of an experienced pitcher is to "take the sting out of the ball," and forcing the batter to hit a groundball is the surest way to do that (Curt Simmons, personal communication).

Nearly all major league pitchers have at least one breaking pitch in their repertoire. Pitching coaches consider a breaking pitch to be an essential ingredient for an effective strategy. Unlike the rising fastball, some kind of breaking pitch can be learned by any pitcher.

Thus, pitchers rely on sudden, rapid vertical movement of their pitches and batters perceive that movement and must contend with it to be successful. . Even great batters (e.g., Aaron and Cohen, 1974) and great pitchers (e.g., Palmer and Cohen, 1975) are convinced that a high fastball can rise and a breaking pitch can drop sharply. But is it just an illusion?

10.2   THE RISING FASTBALL

According to principles of physics, a rising fastball is impossible. Yet, most batters claim it exists and can describe their frustration in attempting to hit this pitch. This widespread belief has persisted in spite of the recognition by a few coaches that such a pitch cannot occur (House, 1994; Thrift and Shapiro, 1990; Mike Scioscia quoted by Will, 1990, p. 91). Our simulation and model explain this contradiction. Although the numbers given in this paper are for professional baseball players, the simulation and model apply to all players, right down to Little Leaguers. They can also be extended to cricket (Regan, 1992). This section on the rising fastball is based on Karnavas, Bahill and Regan (1990) and Bahill and Karnavas (1993).

The rising fastball could be defined variously as a pitch where the ball (1) jumps up, right in front of the plate, (2) crosses the plate above the pitcher's release point, (3) is going upward when it crosses the plate, or (4) falls less than would be expected due to gravity. By definitions (2) and (3), a rising fastball could be thrown by a sidearm baseball pitcher or a softball pitcher, but not with an overhand or three-quarter pitching delivery. For example, an overhand pitch is released about six feet above the ground; if the ball crossed the plate higher than this it would not be a strike. And in order for the ball to be going upward when it crosses the plate, it would have to fall initially, and then near the end of its flight, experience an upward force that is greater than that of gravity. A force that opposes gravity is produced by the backspin on an overhand fastball. However, the maximum spin rate ever measured for a human pitch, 2300 revolutions per minute (rpm), would only create a force two-thirds that of gravity (Watts and Bahill, 2000). So, although a fastball's lift due to backspin may not overcome gravity, it does make it fall less than would be expected due to gravity, which is definition (4). All fastballs fit this definition, making it trivially simple and uninteresting. Therefore, for the rising fastball we will only consider overhand pitches that conform to definition (1).

10.2.1   The Simulation of the Rising Fastball

Figure 10.1a and Table 10.1 show our simulations of 95 and 90 mile per hour (mph) fastballs. Our simulations include the effects of gravity and the aerodynamic forces of lift and drag. In these simulations, both pitches were launched one degree upward with 1500 rpm of backspin. As shown in Fig. 10.1d, the distance between the front of the pitcher's rubber and the tip of the plate is 60.5 feet. But the pitcher releases the ball about 5 feet in front of the rubber. Therefore, for these simulations, the pitcher's release point was 55.5 feet away from the tip of the plate. The bat hits the ball about 1.5
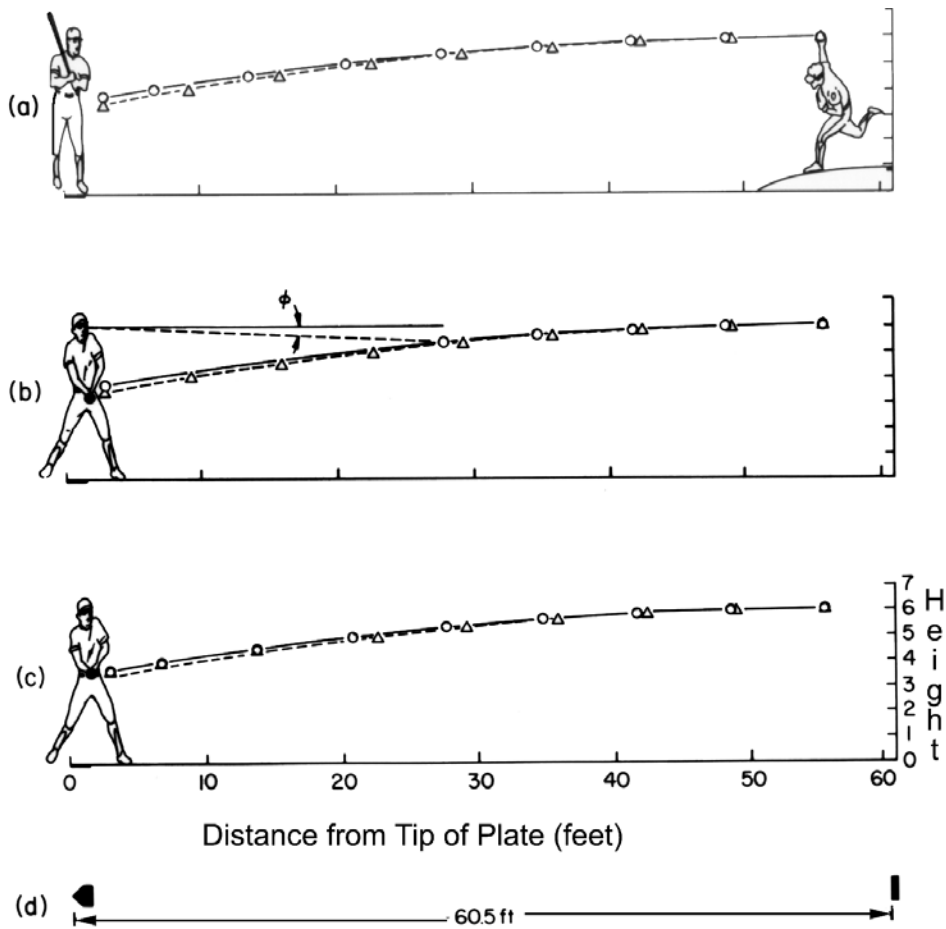
Figure 10.1 (a) Computer simulation of the trajectory of a 95-mph fastball (solid line and circles) and a 90-mph fastball (dashed line and triangles). The slower pitch takes longer to get to the plate and therefore drops more. (b) Computer simulation of the trajectory of a 95-mph fastball (solid line and circles), and the batter's mental model of this trajectory (dashed line and triangles) when the batter underestimated the speed of the pitch by 5 mph. (c) The same simulation as Fig. 10.1b, except that when the ball was 20 feet in front of the plate, the "batter" realized his mental model was wrong and corrected it, thus putting his mental model triangles on the 95 mph trajectory. (d) Physical dimensions for adult baseball. Adapted from Karnavas et al. (1990), pg. 924, with permission of © IEEE.

Table 10.1. Trajectories of Fastballs						
Time Since Release (msec)	95 mph fastball			90 mph fastball		
	Distance (ft)	Height (ft)	Speed (mph)	Distance (ft)	Height (ft)	Speed (mph)
0	55.5	6.00	95.0	55.5	6.00	90.0
50	48.6	5.86	93.3	49.0	5.86	88.5
100	41.8	5.67	91.7	42.5	5.68	87.0
150	35.2	5.43	90.2	36.2	5.44	85.6
200	28.6	5.15	88.6	30.0	5.16	84.3
250	22.2	4.83	87.2	23.8	4.84	82.9
300	15.8	4.46	85.7	17.8	4.47	81.6
350	9.6	4.05	84.4	11.9	4.05	80.4
400	3.4	3.59	83.1	6.0	3.59	79.2
404	3.0	**3.56**	83.0			
426				3.0	**3.33**	78.6

feet in front of the batter's head, which was assumed to be aligned with the front of the plate. The plate measures 17 inches from the back tip to the front edge. So, in these simulations the point of bat-ball collision was 3 feet in front of the tip of the plate, which is represented in the bottom rows of Table 10.1. The pitcher's release point was assumed six feet high. Later, in Table 10.3, we will show how sensitive our conclusions are to these numbers.

10.2.2 The Perceptual Model

The illusion of the rising fastball could be the result of the batter underestimating the speed of the pitch. For example, suppose the pitcher threw a 95-mph fastball, but the batter underestimated its speed and thought it was only going 90 mph. The batter would expect to hit the ball 3.33 feet above the ground (from the sixth column, 426-msec row of Table 10.1). But if the batter were to take his eye off the ball (indicated by the absence of some circles in the actual 95 mph pitch of Fig. 10.1b) and look at his bat in order to see the expected bat-ball collision, then the next time the batter saw the ball it would be 3.56 feet above the ground (third column, 404 msec row of Table 10.1), three inches above his bat. The batter might explain this by saying, "The ball jumped three inches right in front of the plate." Should the batter underestimate the speed at 80 mph, the batter would say the ball jumped one foot. The manager in the dugout, the catcher and the center field TV camera, having different perspectives, would not see this jump.

10.2.2.1 Four Types of Eye Movements

The purpose of the eye-movement systems is to keep the fovea, the region of the retina with the greatest visual acuity, on the object of interest. To accomplish this task, the following four types of eye movements work in harmony: *saccadic* eye movements, which are used in reading text or scanning a roomful of people; *smooth-pursuit* eye movements, used when tracking a moving object; *vergence* eye movements, used when looking between near and far objects; and *vestibulo-ocular* eye movements, used to maintain fixation during head movements. 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 bandwidth are different, and they are affected differently by fatigue, alcohol, drugs and disease. For simplicity, none of the other neural systems associated with vision or eye movement will be discussed in this paper.

The specific actions of these 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 sees a duck, he tracks it using smooth-pursuit eye movements. If the duck lands in the water right next to his boat, he moves 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.

10.2.2.2 Eye Tracking Strategies

Batters use one of two strategies in tracking the pitch (Bahill and LaRitz, 1984). *The optimal learning strategy,* which allows the batter to see the ball hit the bat, is: track the ball over, roughly, the first two-thirds of its trajectory with smooth pursuit eye movements, make a saccadic eye movement to a predicted point of bat-ball collision, continue to follow the ball with peripheral vision letting the ball catch up to the eye, and finally, at the end of the ball's flight, resume smooth pursuit tracking with the images of the ball and bat on the fovea. It is called the optimal learning strategy, because the batter observes the ball, makes a prediction of where it will contact the bat, sees the actual position of the ball when it contacts the bat, and uses this feedback to learn to predict better the next time the pitcher throws that pitch. *The optimal hitting strategy*, which does not allow the batter to see the ball hit the bat, is: track the ball with smooth pursuit eye movements and fall behind in the last five feet. It is called the optimal hitting strategy, because

the batter keeps his eye on the ball longer, which should allow him to make a more accurate prediction of where the ball will cross the plate. We have no evidence that batters voluntarily switch between these two strategies.

It is not surprising that batters do not verbalize their strategies. As you are reading this paper, you typically make three saccades to the right and one to the left for each line of type. But you are probably not capable of explaining your scanning patterns to someone else. Likewise, the batter is probably not capable of stating whether he is using the optimal learning strategy or the optimal hitting strategy.

With the optimal learning strategy, a batter would perceive more rising fastballs because his eyes would not be on the ball (which is why we removed some circles from Fig. 10.1b) when the batter started his swing. This occurs about 150 msec before bat-ball contact, when the ball is about 20 feet in front of the plate. Therefore, during the pitch the batter could not discover inaccuracies in his estimation of pitch speed and make adjustments. Whereas, with the optimal hitting strategy, a batter would perceive fewer rising fastballs because his eye would be on the ball when it was 15 to 25 feet from the plate. Therefore, the batter could sense inaccuracies in his speed estimation and, as shown in the last 150 msec of Fig. 10.1c, make an appropriate correction, such as checking his swing.

The batter performs a different operation in each third of the pitch's flight: observe, compute and swing. For the rising fastball, as the batter observes the ball for the first third of its flight, he underestimates the pitch-speed and, therefore, miscomputes the height of the bat-ball collision. Then, at the start of his swing, the batter takes his eye off the ball to look at the estimated bat-ball collision point. When the ball comes back onto his fovea it is higher than the batter thought it would be.

In the next section, we develop a neurophysiological model to investigate the perceptual illusion of the rising fastball. This model of the human visual processing is based on (Todd, 1981: Regan, 1986: Karnavas, Bahill and Regan, 1990: Regan, 1992: Bahill and Karnavas, 1993) and uses only experimentally verified primary visual processes.

10.2.3 The Neurophysiological Model

The batter must precisely predict the location of the ball in four-dimensional space: t, the time coordinate and the x, y and z spatial coordinates shown in Fig. 10.2. To hit the ball the batter must predict *when* and *where* it will cross the plate. Bunting the ball is analogous to catching the ball with a bat. In this act, the batter does not need to predict **both** when and where; because when is not important. The batter has only one task:

predicting *where* the ball will be. And this task is much simpler; thus, most bunt attempts make contact with the ball.
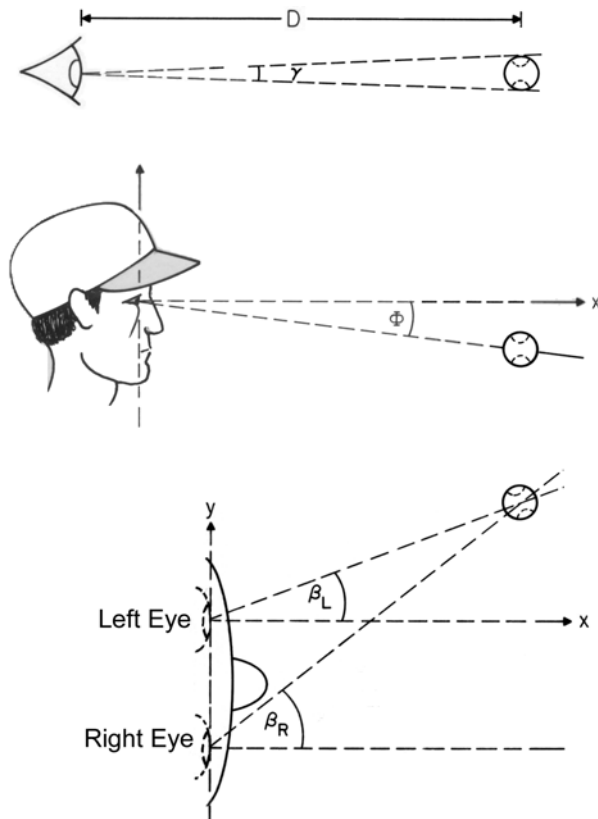

Figure 10.2. Visual system parameters used by the batter: (top) angular size of the baseball, γ, the batter has no direct means to sense the distance to the ball (*D*); (middle) distance of the ball's image off the batter's fovea, Φ; and (bottom) horizontal angle of the right and left eyes, β_R and β_L. Adapted from Karnavas et al. (1990), pg. 925, with permission of © IEEE).

10.2.3.1 Predicting When

Let us see how the batter who is swinging at a pitch can judge *when* the ball will be crossing the plate. In his novel The Black Cloud, Sir Fred Hoyle (1957) showed that the time until contact with an object moving along the line-of-sight can be approximated by the equation

$$\text{time until contact} \approx \frac{\gamma}{d\gamma / dt} \tag{10.1}$$

where γ and $d\gamma / dt$ are respectively the object's angular size and rate of change of angular size. Lee (1976) subsequently gave the label tau (τ) to the right side of the equation and suggested that estimations of time until contact that are used to control motor actions are based on this variable. For example, it has been shown that birds use τ when diving into the water to catch prey, and athletes use τ when jumping to hit a dropped ball, adjusting strides when running hurdles and timing their swings in table tennis; for these tasks time until contact is judged with an accuracy around 2 to 10 msec. Cricket players time their swings with an accuracy of ±5 msec (Regan, 1992). Top sports players estimate the time until contact of the bat and ball with an accuracy of better than three msec (Regan, 1997; Gray and Regan, 1998). The batter's calculation of time until contact has three sources of error. First, Eq. 10.1 is only an approximation because it uses the approximation $Tan\Psi = \Psi$. Second, the ball is not headed directly at the batter's eye. In our simulations, these two sources produced errors of about one msec at the start of the swing. The third source of error, which results from the batter hitting the ball 1.5 feet in front of his eyes, produces a constant 11 msec of error in underestimating the time of arrival at impact.

The human visual system can implement Eq. 10.1. First, there is psychophysical evidence that the human brain contains units tuned to size (γ), and size-tuned neurons have been found in monkey visual cortex. Second, psychological studies have shown that the visual system has specialized "looming detectors" that compute $d\gamma / dt$ independent of the object's trajectory (Regan and Beverley, 1978, 1980). Furthermore, specific brain neurons are sensitive to changing-size, $d\gamma / dt$ (Regan and Cynader, 1979; Saito et al., 1986). Using these two pools of neurons, the brain could compute τ.

Is the movement of the baseball within physiological thresholds? For objects subtending less than 1.5 deg, $d\gamma / dt$ as low as 0.02 deg/sec can be detected (Regan and Beverley, 1978). Lee (1976) suggested a threshold of 0.08 deg/sec. When the pitcher releases a 95 mph fastball, γ is ¼ deg and $d\gamma / dt$ is 0.66 deg/sec. Therefore $d\gamma / dt$ is well above visual threshold from the moment the ball leaves the pitcher's hand. The value of γ remains below 1.5 deg until the ball is ten feet from the tip of the plate. Figure 10.3 shows how γ and $d\gamma / dt$ change during the flight of the ball. The arrows indicate the points where they cross their thresholds.

In this section, we proposed a model for estimating time until contact. We showed that the human brain has neuronal circuitry that could do the

needed computations. And we showed that the parameters of a pitch are within physiological thresholds for these neuronal circuits. Next, we assert that people can accurately estimate time until contact using Eq. 10.1 alone. In experiments reported by Gray and Regan (1998), observers using only Eq. 10.1 were able to estimate time until contact with errors of 2 to 12%. As we have stated before, the pitch can be divided into thirds. During the first third, the batter gathers sensory information; during the middle third, a computation is made of where and when the ball will make contact with the bat; and the final third is the swing of the bat. With this scenario, the batter would have to use information gathered in the first third of the pitch to estimate time until contact. For a 95 mph fastball with a duration of 404 msec, this would be 268 msec before contact. A 2% estimation error corresponds to a temporal error of 5 msec, which is within the required temporal error of 9 msec computed by Watts and Bahill (2000). The 2% error is at the low end of the 2 to 12 % range given by Gray and Regan. It has been shown before (Bahill and LaRitz, 1984) that professional athletes usually perform at the optimal end of the range of values found in laboratory experiments. Using other estimators for time until contact might improve accuracy, as discussed below.
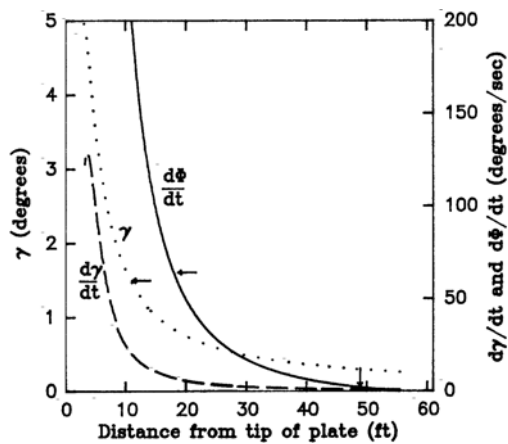

Figure 10.3. Physiological clues to ball position, γ, $d\gamma/dt$ and $d\Phi/dt$, as functions of distance to the tip of the plate, for a 95 mph fastball. Adapted from Bahill and Karnavas (1993) with permission of Journal of Experimental Psychology, Human Perception and Performance.

Time until contact can be estimated using Eq. 10.1. It can also be estimated using binocular disparity (δ) according to

$$\text{time until contact} \approx \frac{I}{Dd\delta/dt} \qquad (10.2)$$

where I is the interpupillary separation and D is the distance to the ball (Gray and Regan, 1998). When a 90 mph fastball is 40 feet from the plate, $d\delta/dt$ is about 0.8 deg/sec, which is above discrimination threshold. Gray & Regan (1998) found that estimates of time until contact for a simulated approaching ball are more accurate when based on a combination of Eqs. 10.1 and 10.2 than for either cue alone suggesting that a hitter might estimate time until contact of an approaching ball more accurately if both these sources of information were used. It is not known whether or how they are combined during baseball batting, however.

We conclude that from the instant the ball leaves the pitcher's hand, the batter's retinal image contains accurate cues for time until contact, and that the human visual system is capable of utilizing these cues. Evidentially most batters estimate when the ball crosses the plate with an accuracy of ± 9 msec, otherwise the ball would be hit foul. Next, we want to consider the more difficult issue of judging *where* the ball will be at the time of bat-ball contact

10.2.3.2 Predicting Where

To hit the ball the batter must predict both *when* and *where* it will cross the plate. Let us now see how the batter can judge *where*.

It is important to note that the batter has no direct visual access to the *x, y* and *z* spatial coordinates: the batter's judgments must be based entirely on retinal image data. The relevant retinal parameters are the angular size of the ball, γ, and the angular distance of the ball's image off the fovea, Φ, shown in Fig. 10.2, and their time derivatives $d\gamma/dt$ and $d\Phi/dt$. We assume the batter's eyes are in the x-y plane as shown in Fig. 10.2, although the Pittsburgh Pirate studied by Bahill and LaRitz (1984) actually rotated his head 23° in pitch and 12° in roll.

The batter can estimate the ball's height at contact from the ball's vertical speed and the time until contact. The batter can estimate the ball's vertical speed from the retinal velocity and the distance to the ball. The smallest value of retinal velocity, $d\Phi/dt$, that can be detected is about 0.02 deg/sec. Over a range of moderate speeds, between about 2 and 64 deg/sec, the discrimination of differences in $d\Phi/dt$ is within 5% (McKee, 1981; Orban et al. 1984). Figure 10.3 shows that for a 95 mph pitch the value of $d\Phi/dt$ reaches 0.02 deg/sec before the ball has traveled one foot, reaches 2 deg/sec 49 feet from the tip of the plate, and reaches 64 deg/sec 18 feet from the tip

of the plate. Therefore, the batter can make discriminations of $d\Phi/dt$ that diminishes only after the swing has begun. (The swing starts when the ball is about 19 feet away from the bat-ball contact point.)

Now comes the crucial element in our explanation of the illusion of the rising fastball. Although retinal image information provides an accurate cue for the ball's time until contact, it provides poor cues to the absolute distance to the ball (D in Fig. 10.2a) and for its line-of-sight speed. Classical stereoscopic depth perception is of little help in this regard: although the stereoscopic depth system provides a precise indication of relative depth (i.e. the difference between the x-axis distances of two objects imaged near the fovea), it provides little indication of absolute distance. In tracking the pitched ball, the batter has one object, the ball, imaged on his fovea. Therefore, the batter cannot measure the distance to the ball or the pitch speed; the batter can only estimate them.

Our psychophysical explanation for the rising fastball is as follows. The batter can estimate pitch speed and the time since the ball left the pitcher's hand. The batter can use these data in conjunction with his experience to estimate the distance to the ball ($\hat{D}$). The "hat" on top of a symbol indicates that it is an estimate. The batter can then use this estimate for distance and the ball's retinal image velocity $d\Phi/dt$ to estimate the vertical velocity $d\hat{z}/dt$. From the vertical velocity and the time until contact (τ) the batter can estimate how far the ball will fall in the last part of its flight, and therefore estimate the height of the ball when it crosses the front edge of the plate. For example, suppose the pitcher enhances the batter's expectations with a series of 90 mph pitches, and then throws an unusually fast 95 mph pitch. Assume the batter uses a 90 mph mental model to interpret the retinal image information about the 95 mph pitch. Suppose the batter tried to estimate the ball's vertical speed 250 msec after the ball left the pitcher's hand. If the actual pitch were a 95 mph fastball, it would be 20.7 feet from his eye, subtracting 1.5 feet (the distance between the tip of the plate and the batter's eye) from the x distance of 22.2 in Table 10.1. Its vertical velocity of -8 ft/sec (from velocity = gt) would, at this distance, produce a retinal velocity of -21 deg/sec. However, if the batter thought the pitch was a 90-mph fastball, this would translate to 22.3 feet away at 250 msec after release. At this distance, a retinal image velocity of -21 deg/sec would indicate that the vertical velocity was about -8.6 ft/sec. So the batter would think the ball was falling faster than it really was and would probably swing under the ball. Therefore, if the batter made a saccadic eye movement to a predicted point of bat-ball contact, this point would be below the ball when the ball caught up with the eye, and the ball would seem to have jumped upwards, in this example by three inches. To be sure, this error of visual judgment could be avoided if the batter had an accurate visual cue to the ball's absolute distance

(*D*) or its speed, but, as we have seen, the batter is essentially "blind" to these two important parameters. Blind means he as no direct optical sense for these two parameters: he must estimate them using other retinal image data.

This model can be summarized with Fig. 10.4 and Eq. 10.3,

$$\hat{z}_{\text{fall}} = (\hat{D}_0 - \hat{t}_{\text{sinceRelease}}\hat{s})\left(\frac{d\Phi}{dt}\frac{\gamma}{d\gamma/dt}\right)$$ (10.3)

where $\hat{z}_{\text{fall}}$ is the estimate of how much further the ball will fall before contact, $\hat{D}_0$ is the estimated distance between the ball and the batter's eye at the time of release, $\hat{t}_{\text{sinceRelease}}$ is the estimated time since release, $\hat{s}$ is the estimated pitch speed, $d\Phi/dt$ the retinal image velocity, γ is the retinal image size, and $d\gamma/dt$ is the rate of change of retinal image size. The model of Fig. 10.4 shows how the batter's brain can predict how much further the ball will fall before its contact with the bat. Summation (Σ symbol in a circle), division ($\div$ sign in a pentagon) and multiplication ($\times$ sign in a pentagon) can be accomplished by brain circuitry. Symbols with hats ($\wedge$) are estimates.
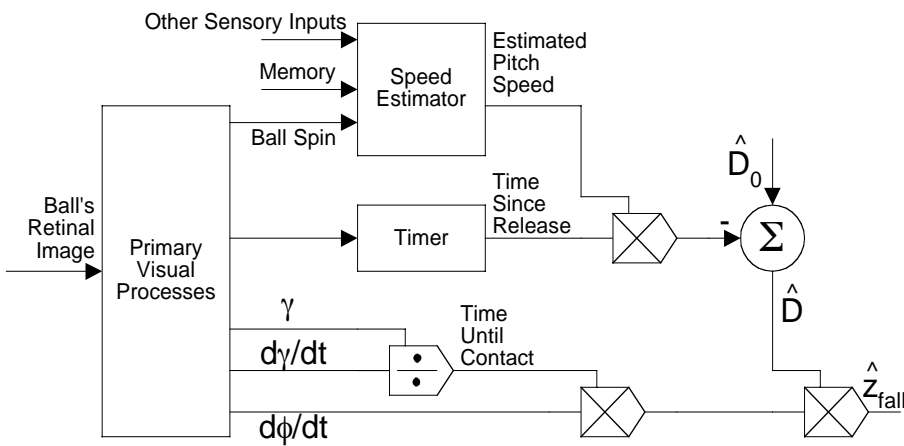

Figure 10.4. A model for a batter estimating the height of the ball at the time of its collision with the bat. The input to the system is the ball's retinal image and its output is the estimate of how much further the ball will fall before contact with the bat. Adapted from Bahill and Karnavas (1993) with permission of Journal of Experimental Psychology, Human Perception and Performance.

The first term of Eq. 10.3 is the estimated distance to the ball at the moment of prediction, $\hat{D}$, and the last term is τ from Eq. 10.1, so Eq. 10.3 can be rewritten as

$$\hat{z}_{\text{fall}} = \hat{D}\frac{d\Phi}{dt}\tau \qquad\qquad\qquad (10.4)$$

Overestimating any one of these three terms could produce the illusion of the rising fastball. But, as we have already shown, batters can accurately perceive $d\Phi/dt$ and estimate τ; the difficulty is in estimating the distance to the ball. And in this model, they use estimated pitch speed to estimate the distance to the ball. That makes the speed estimator in Fig. 10.4 the crucial element of this model. In order to estimate the height of the ball at the time of contact, the batter must be able to estimate the pitch speed. But pitch speed cannot come from the primary visual processes. The speed estimator receives inputs from the primary visual processes, such as ball spin. The speed estimator probably uses memory and other sensory inputs such as the motion of the pitcher's arms and body, or a sign from a base runner on second who has stolen the catcher's signals.

The speed estimator might be most accurate just after the pitcher releases the ball, for at this point, the batter should be able to estimate its distance $\hat{D}_0$ quite well. And the distance $\hat{D}_0$ combined with the time until contact would provide the speed. But at this time, the estimation of the ball's height at the time-of-contact may still be in error, because retinal image velocity $d\phi/dt$ is inaccurate until the ball is 49 feet from the tip of the plate.

We considered many other signals that might be used to help estimate the speed of the ball and its distance, but we discarded them because they were inappropriate. For example, the retinal image could contain a cue to line-of-sight speed dD/dt because $dD/dt = (D/\gamma)(d\gamma/dt)$. And, as we have already shown, the batter has visual clues for γ and $d\gamma/dt$, but unfortunately the batter has no reliable visual cue to absolute distance D, so the batter is unable to take advantage of the geometrical fact expressed in this equation. We considered many techniques for estimating the distance to the ball. (1) The vergence eye movement system (the difference between β_L and β_R in Fig. 10.2c) cannot help, because vergence changes do not contribute to motion-in-depth sensation (Regan et al., 1986). (2) The differences in the batter's lines-of-sight for the two pitches of Fig. 10.1 do not differ by one degree until the ball is 6 feet from the batter, and extra-retinal sensation of eye position is only good to about one degree (Matin and Kibler, 1966; Steinbach, 1970). (3) Parallax is often used to help judge distance. However, the batter only starts his translational head movements in the last third of the ball's flight (Bahill and LaRitz, 1984; Watts and Bahill, 2000) and this is too late to help him. (4) We have already commented that stereoscopic depth perception only gives clues about the relative depth of

two objects and not about absolute distance to a single object, so it cannot help and is, in fact, not necessary for good hitting. Indeed, according to Kara (1990), an ophthalmologist who examined him, Babe Ruth was amblyopic and never had more than 20/200 vision in his left eye. Therefore, we conclude once again that the batter has no information to determine accurately the ball's absolute distance (*D*) from his eye.

We have said before that the batter must predict both *when* and *where* the bat-ball collision will occur. To hit a line drive in fair territory, the batter must estimate *when* to within ± 9 msec and *where* to within ± ½ inch (Watts and Bahill, 2000). Comparing these numbers to the 22-msec and 2.8 inch differences between the 90 and 95-mph fastballs, we see that estimating *where* requires greater percent accuracy. But batters seem to be more accurate at estimating *when*. Indeed few line drives are hit into foul territory (accurate position but poor timing), whereas many foul tips and pop ups are hit into foul territory (poor accuracy and poor timing). Fig. 10.4 suggests an explanation: *when* (τ) can be computed from primary visual processes, whereas the pitch speed, and therefore *where*, can only be estimated. So *where* is the crucial parameter: it requires greater precision, yet it cannot be calculated from primary visual processes, it can only be estimated.

Although we developed this model to explain the illusion of the rising fastball, it might also be applied to other pitches. For example, the change up is only effective if it fools the batter and makes him overestimate the pitch speed. According to our model, this would make the batter swing over the ball. Our model predicts that effective change ups to right-handed batters should result in ground balls to the left side of the infield.

The existence of the speed estimator in Fig. 10.4 enables predictions that (1) large variations in speed from pitch to pitch should lead to large spatial errors in the swing, (2) unexpectedly fast pitches (e.g., when a fast pitch follows a sequence of slow pitches or a fast pitch is thrown on an unexpected count) should cause the batter to swing under the ball, (3) unexpectedly slow pitches (e.g. a change up) should cause the batter to swing over the ball and (4) the sequence of recent events should influence performance. All of these predictions from the model were supported by Gray (2002). They also are manifest in the philosophies of great pitchers – Warren Spahn is quoted by Will (1990) as saying, "Hitting is timing. Pitching is upsetting timing."

10.3   EXPERIMENTAL ASSESSMENT OF THE MODEL

To help assess the performance of the model Bahill and Karnavas (1993) ran experiments using a mechanical pitching machine. They threw 450 pitches to seven subjects: three adults and four boys aged 9, 11, 11 and 13. Nominally, the speed of the machine was set for 50 mph, but occasionally it threw a fast pitch at 55 mph. The number of normal pitches between these fast pitches was randomly chosen from amongst 3, 4, 5, and 6. An observer (who did not know the pattern of normal and fast pitches) recorded the relationship of the bat and ball when the ball crossed the plate. They averaged the results of the fast pitches and of the two pitches before and after, as shown in Fig. 10.5. These data show that on the fast pitches the batters swung below the ball, which is just what would happen if they underestimated the speed of the pitch. It was statistically significant that when the unusually fast pitch was thrown, the batters underestimated the speed and swung under the ball. This is precisely the illusion of the rising fastball.
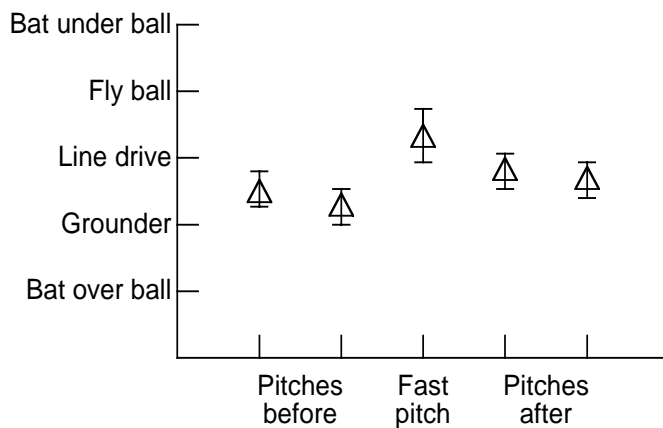

Figure 10.5. Averaged data from seven batters showing that when an unusually fast pitch was thrown most batters swung under the ball. The triangles are the mean values and the vertical bars are the 95% confidence intervals.

10.4   THE BREAKING CURVEBALL

There is no longer a controversy about whether or not a curveball curves; it does, because it obeys the laws of physics. These laws say that the spin of the ball causes the curve (Watts and Bahill, 2000; Fig. 10.6). Should this spin be horizontal (as on a toy top) the ball curves horizontally (of course it also drops due to gravity). If it is top spin, the ball drops more than it would due to gravity alone. Else, if it is somewhere in between, the ball both curves and drops. In baseball, most curveballs curve horizontally and drop vertically. The advantage of the drop is that the sweet area of the bat is about four inches long but only an inch high. Thus, a vertical drop would be more effective at taking the ball away from the bat's sweet area than a horizontal curve. We now want to present the principles of physics that explain why the curveball curves.
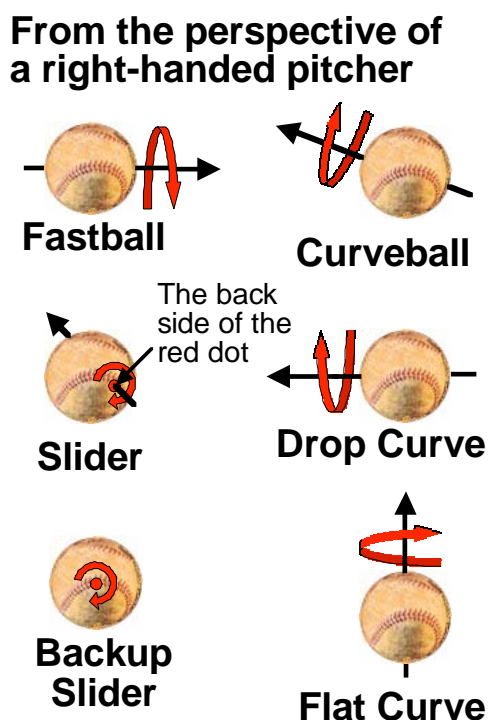
From the perspective of a right-handed pitcher

Fastball

Curveball

The back side of the red dot

Slider

Drop Curve

Backup Slider

Flat Curve

Figure 10.6. The axis of rotation for several pitches.

The first part of our explanation invokes Bernoulli's Principle. When a spinning ball is placed in moving air, as shown in Fig. 10.7, the movement of the ball and its seams slows down the air flowing over the top of the ball and speeds up the air flowing underneath the ball. Now, according to Bernoulli's Equation, the point with lower speed (the top) has higher pressure, and the point with higher speed (the bottom) has lower pressure. This difference in pressure pushes the ball downward.
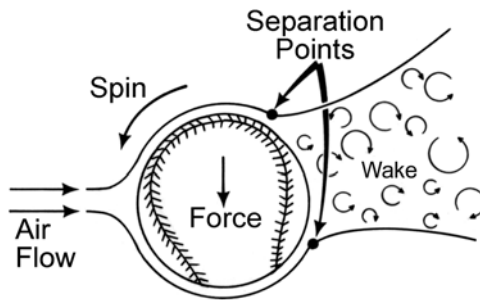
Figure 10.7. Air flows smoothly around the ball until it gets to the separation points. There the airflow changes into a turbulent wake that is deflected upward in this figure. If this were a top view, it would explain the curve of a ball. If it were a side view, it would explain the drop of a ball.

Our second (and probably better) explanation involves the principle of Conservation of Momentum. As shown in Fig. 10.7 the wake of turbulent air behind the ball is deflected upward. You can see such wakes behind boats. In a boat, swinging the rudder to the right deflects water to the right, and to conserve momentum the back of the boat must be pushed to the left. You can feel this force if you put your hand out the window of a moving car. (Make sure the driver knows you are doing this!) Tilt your hand so that the wind hits the palm of your hand at an angle. This deflects the air downward, which causes your hand to be pushed upward. Tilt your hand so that the wind hits the back of your hand. This deflects the air upward, which causes your hand to be pushed downward. Now let us relate this to the spinning baseball in Fig. 10.7. Before the ball interacts with the air, all the momentum is horizontal. Afterwards the air in the wake has upward momentum. The principle of conservation of momentum therefore requires that the ball have downward momentum. Therefore, the ball will curve downward.

There are several ways to shift the wake of turbulent air behind a baseball. The wake is shifted by the spin on a curveball. The friction that slows down the flow of air over the top of the ball causes the air to separate from the ball sooner on the top than on the bottom, as shown in Fig. 10.7. This shifts the wake upward, thus pushing the ball downward. For nonspinning pitches, such as the knuckle ball and the scuff ball, when the seams or the scuff are near the bottom separation point they create turbulence, which delays the separation, as shown in the bottom of Fig. 10.7, again shifting the wake upward, and pushing the ball downward.

So, when the pitcher puts spin on the ball, the wake of turbulent air behind the ball is moved to one side, causing the ball to curve, thereby confounding the poor batter who is trying to hit it.

Now let us return to the breaking curveball. Baseballs (except for knuckleballs etc.) follow smooth parabolic trajectories. The 90-mph fastball of Table 10.1 and Fig. 10.1 falls more than two and one-half feet in its flight to the plate. A plot of this vertical distance as a function of time would be parabolic. The ball falls 3.8 inches in the first 100 msec, 6.2 inches in the second 100 msec, 8.3 inches in the third 100 msec, and 10.3 inches in the fourth 100 msec. The ball drops more in each time period, but it follows a smooth parabolic trajectory. Now let us see how the ball drops with the addition of a vertical force due to top spin on the ball. Table 10.2 shows the results of simulations of 80 and 75-mph drop curves. We are going to use the term *drop curve* for a pitch with pure top spin. Both were launched at an angle of 2.5 degrees up with 1900 revolutions per minute (rpm) of pure top spin. We used the following formula from Watts and Bahill (2000) for the downward force due to spin: $F = ? \rho \pi R^3 \omega v$, where ρ is the air density, R is the radius of the baseball, ω is its spin rate and v is its velocity.

Let us look at the 75-mph pitch. The ball falls 2.4 inches between 100 and 200 msec, 7.7 inches in the next 100 msec, 12.7 inches in the next 100 msec, and 17.5 inches in the next 100 msec. Once again, the ball drops more in each time period, but it still follows a smooth parabolic trajectory. Therefore, this is a gradual curve rather than a sharp break. This conclusion is shared by Adair (p. 31, 1990) who stated, "Like its cousin, the curve ball, the hopping fastball follows a smooth arc on its way to the plate, but half of the hop deviation occurs in the last 15 feet of that flight." A breaking pitch would have to drop the same amount as this ball in the early 100-msec epoch, but more than this in the last 100 msec. It would be impossible to hit the ball if it really did jump or break just before reaching the plate. For example, a foul tip changes the ball's trajectory abruptly in the last few feet before the catcher and the umpire. As a result, these masked men cannot predict the ball's trajectory and they must wear protective clothing.

Table 10.2. Drop curve Trajectories				
	80 mph		75 mph	
Time Since Release (msec)	Distance (ft)	Height (ft)	Distance (ft)	Height (ft)
0	55.5	6.00	55.5	6.00
50	49.7	6.20	50.0	6.18
100	44.0	6.28	44.7	6.25
150	38.3	6.24	39.4	6.20
200	32.7	6.09	34.1	6.05
250	27.2	5.83	29.0	5.78
300	21.9	5.47	23.9	5.41
350	16.5	4.99	18.8	4.93
400	11.3	4.41	13.9	4.35
450	6.11	3.73	9.0	3.67
480	3.0	3.27		
500			4.2	2.89
513			3.0	2.68

We are now ready to explain the apparent abrupt break of some pitches. Suppose the pitcher threw the 75-mph drop curve of Table 10.2, it would drop 25 inches in the last 150 msec before contact. However, if the batter overestimated the pitch speed and thought it was going 80 mph, then the batter would expect it to fall 21 inches in the last 150 msec before contact. Thus, if the batter took his eye off the ball 150 msec before the projected time of contact, and saw it again when it arrived at his bat, he would think that it broke downward 4 inches. Therefore, we suggest that the apparent, abrupt-break of some pitches might be a result of the batter's **over**estimation of the speed of the pitch in his mental model. This is the opposite of the explanation for the rising fastball.

Of course, the illusion would be greatly enhanced if the batter made a mistake in estimating both the speed and the type of the pitch. If the pitch were a 95 mph fastball with 1600 rpm of backspin and the batter thought it was a 75 mph drop curve with 1900 rpm of top spin, then the illusionary jump would be one foot. Similarly, if such a drop curve were mistaken for such a fastball, then the illusionary break would be one foot.

In summary, we think every pitch (except a nonspinning pitch such as the knuckle ball) follows a smooth trajectory. The apparent, abrupt jumps and sharp breaks right before the plate are perceptual illusions, caused by the batter using the optimal learning strategy of tracking and making mistakes in

his mental model of the pitch. We think that in the first third of the ball's flight, batters gather data and form mental models of the pitch. In the middle third, batters compute when and where the ball will cross the plate. Then they start their swings. In the last third of the ball's flight, the batters either observe errors in their mental models so that they can track the next pitch better (the optimal learning strategy), or they update their mental models and perhaps check their swings (the optimal hitting strategy).

10.5   THE EFFECTS OF SPIN AND SPEED

Batters say that the ball hops, drops, curves, breaks, rises or tails away. They say that the pitcher throws a fastball, curveball, drop curve, flat curve, slider, backup slider, change up, split fingered fastball, splitter, forkball, sinker, two seam fastball or four seam fastball. This sounds like a lot of variation. However, no matter how the pitcher grips or delivers the ball, once it is in the air (excepting the knuckleball), its motion depends only on its (1) speed, (2) rate of rotation and (3) direction of the axis of rotation. As shown in Fig. 10.6 and previously discussed, the curveball has top spin and side spin, so from the perspective of a right-handed pitcher, it drops and curves right to left. The fastball has predominately backspin, which gives it lift and decreases the fall due to gravity. But if it were not thrown with an overhand delivery, then it would also have some lateral deflection. The slider is thrown like a football, which causes it to spin like a bullet. If its axis of rotation is coincident with the direction of motion, then the spin causes no deviation. Therefore, the slider is usually thrown so that the axis of rotation is pointed up and to the left. This causes the ball to drop and curve right to left. Rotation about this axis allows the batter to see a red dot on the top-right-side of the ball. For the backup slider, the axis of rotation is coincident with the direction of motion: the spin causes no horizontal curve and the batter sees a red dot right in the middle of the ball. The drop and curve of all these pitches is infinitely variable depending on the axis of rotation.

The black arrows in Fig. 10.6 indicate the vector moment of the spin. You can determine the direction of the spin-induced deflection using the right-hand rule. Point the thumb of your right hand in the direction of the black arrow and point your index finger in the direction of motion of the pitch. Bend your middle finger so that it is perpendicular to your index finger. Your middle finger will be pointing in the direction of the *spin-induced* deflection (of course the ball also drops due to gravity).

Besides spin, speed also characterizes the movement of the ball. The purpose of changing pitch speeds is not to fool the *when* computer, but rather to fool the speed estimator and consequently the *where* computer.

A 90 mph fastball is in the air 426 msec, so it drops 2.8 feet due to gravity ($\frac{1}{2} at^2$) but the backspin lifts it 1 foot, producing a total drop of 1.8 feet. Whereas a 75 mph drop curve is in the air 511 msec, so it drops 4 feet due to gravity and the top spin drops it an additional 1.6 feet, producing a total drop of 5.6 feet. (These numbers are different from those in Tables 10.1 and 10.2 because here both of these pitches were launched horizontally, that is with a launch angle of zero.)

So changing from backspin to top spin drops the ball 2.6 feet. Whereas changing the speed from 90 mph to 75 mph drops the ball 1.2 feet. These are very large distances compared with the vertical margin of error on the sweet area of the bat.

For these simulations of Section 10.5, the pitch was launched horizontally to avoid confounding effects of an upward launch. However, in order to cross the plate in the strike zone almost all pitches much be launched with an upward angle. Fastballs by Randy Johnson are possible exceptions. He is tall enough and fast enough to pitch some fastballs with a downward launch angle and still have them go through the strike zone. Such fastballs must seem strange to a batter.

10.6 SENSITIVITY ANALYSES

To help validate our simulation and model we will now investigate how well our conclusions hold up under parametric sensitivity analyses. First, we will show the results of a sensitivity analysis of our simulation (Fig. 10.1 and Tables 10.1 and 10.2), and then we will show the results of a sensitivity analysis of our model of the human brain (Fig. 10.4).

Each of the eight simulation parameters was varied by ±5%. Then we ran the simulation and calculated the percentage change for the perceived jump. The ratio of these two percentages is the relative sensitivity (Karnavas, Sanchez and Bahill, 1993). These sensitivity values are shown in the top of Table 10.3.

To understand these numbers, it is helpful to note from our nominal simulation results (Table 10.1) that the apparent jump of the rising fastball is 0.230 feet. When the horizontal position of the bat-ball collision point was moved back 5%, the amount of perceived jump increased to 0.231 feet, or by 0.5%, which is -0.1 (the value of the sensitivity coefficient from Table 10.3) times 5% (the perturbation size). Similarly, when the estimated pitch speed was decreased 5%, the amount of perceived jump increased to 0.472 feet, or by 105.4%, which is 21.1 times 5%. *Therefore, the simulation is most sensitive to pitch speed and the estimated pitch speed; in comparison, all other parameters are insignificant.*

Table 10.3. Results of Sensitivity Analyses	
Sensitivity Coefficients for the Simulation	
Parameter	Value
Horizontal position of the pitcher's release point	-0.2
Vertical position of the pitcher's release point	0.0
Release angle	0.0
Horizontal position of the batter's eye	0.0
Vertical position of the batter's eye	0.0
Horizontal position of the bat-ball collision	-0.1
Pitch speed	18.9
Estimated pitch speed	-21.1
Sensitivity Coefficients for the Model	
Parameter	Value
$\hat{D}_0$, estimated distance to release point	-2.57
$\hat{t}_{sinceRelease}$, estimated time since release	1.57
$\hat{s}$, estimated pitch speed	1.57
$d\Phi/dt$, retinal image velocity	-1.00
γ, retinal image size	-1.00
$d\gamma/dt$, rate of change of retinal image size	0.95

It is rewarding to see that the pitch speed and the estimated pitch speed are the most important parameters of the simulation. The sensitivity analysis tells us that we should not (1) try to get more accurate values for the other parameters of the simulation, (2) customize the simulation for individual players, or (3) try to get more accurate values for the thresholds of the visual parameters γ or $d\theta/dt$, because these parameters are not that important. The bottom line of this analysis is that our simulation is a good representation for the pitched baseball.

Next, we did a sensitivity analysis of our neurophysiological model of Fig. 10.4 for a 90 mph pitch. Each of the six model parameters was varied by ±5%, and we calculated the percentage change in how far the ball dropped between 250 msec after release and the time of bat-ball contact. The ratio of these two percentages is the relative sensitivity. These sensitivity values are shown in the bottom of Table 10.3.

The model is most sensitive to the three parameters that are used to estimate the distance to the ball. The batter cannot get these parameters from the primary visual processes. It seems that the model is most sensitive to the

things that are most difficult for the human to compute. Perhaps superior athletes are superior not because they have superior primary visual processes, but because of their subsequent processing of this information.

From these studies, we can see that estimating pitch speed is essential for the batter to achieve what Charley Lau describes as "the sweet spot in time" – that instant when the sweet area of the bat is in the right place to meet the sweet spot of the ball (Lau and Glossbrenner, 1984). It seems that a useful training technique would be to put a speech synthesizer on a radar gun behind the plate in the batting cage and announce the speed immediately after every pitch during batting practice. This might help the batter learn to estimate pitch speed better.

10.7   THE TWO-SEAM AND FOUR-SEAM FASTBALLS

Tom Seaver (Seaver and Lowenfish, 1984) has written that the four-seam grip is more effective in producing rising fastballs than the two-seam grip. However, wind tunnel tests have shown no difference in lift between the two-seam and the four-seam fastballs (Watts and Bahill, 2000, p. 75). Perhaps the explanation for this apparent contradiction could be based on psychology instead of physics.

As the frequency of a blinking light increases, it appears to flicker and then at a certain frequency it appears to be continuously illuminated. This transition point is called the Critical Flicker Fusion Frequency. For a person in a baseball park this frequency is probably between 40 and 50 Hz. Television screens present a new frame sixty times per second (60 Hz); therefore, their pictures do not flicker, whereas the time indicator on your VCR probably blinks once a second. This is clearly perceived as blinking.

If a fastball were rotating at 1200 rpm, it would rotate 20 times per second. For a two-seam fastball, there would be two seams crossing the field of view on each rotation (or, because the seams are close together, they might appear as one blip). So, the frequency would be between 20 and 40 Hz, which is below the critical flicker fusion frequency and perhaps the ball would appear to flicker. Therefore, the batter could detect the spin. He does not have to compute the spin rate: he just has to determine if it is top spin (a curveball) or backspin (a fastball). This would help his speed estimator of Fig. 10.4. In contrast, for a four-seam fastball, the four seams would cross the field of view symmetrically for each rotation. This would produce a frequency of 80 Hz, which is above the critical flicker fusion frequency. The ball would be seen as a blur and the batter would not be able to detect the direction of spin. Therefore, the batter would have to guess if it were a

curveball or a fastball. If he guesses that it is a curveball, then he will think it is slower than it is and might perceive a rising fastball.

Almost all pitchers who use an overhand or three-quarter delivery throw four-seam fastballs and curveballs. The ball is gripped with the index and middle fingers extending across four seams. They say that each seam is a ridge that provides high impedance to the airflow around the ball when the seam is perpendicular to the direction of flight. They say that backspin with four seams perpendicular to the trajectory gives the ball maximum "lift." The four-seam pitch is probably harder to hit than a two-seam pitch. But the reason may come from Psychology, not Physics. The four seam pitches produce a flicker frequency that is too high for batters to discern the movement of the seams.

Some great hitters have stated that they do not see the direction of spin on the pitch. For example, Tony Gwynn (Gwynn and Rosenthal, 1992) has stated, "I'm not like a lot of hitters who see the ball spin a certain way on a particular pitch. I just see the ball." Frank Robinson (as quoted in Schmidt and Ellis, 1994) said, "I think the initial reaction [to the ball] coming out of the hand is an advantage over waiting to see the seams of the ball." And Mike Schmidt (Schmidt and Ellis, 1992) wrote, "So many people say that the hitter sees the spin of the ball, the seams. I don't believe it. I couldn't." Against pitchers using four-seam grips, batters are forced to determine the kind of pitch from other cues (such as the pitcher's release point and the early trajectory of the ball) rather than the direction of spin (Baker, Mercer, and Bittinger, 1993).

10.8   STRATEGIES

10.8.1   Strategies, Heuristics and Processes of the Batter

On each pitch, the batter is trying to accomplish some task. To do this he uses one or more strategies, such as "Predict the Pitch," "Protect the Plate," "Take the Pitch," "Go for the Long Ball," "Protect the Base Runner," "Hit to the Opposite Field" or "Make Contact." These strategies provide the objectives for the batter's cognitive processes (anticipatory modeling of the pitch, tracking the pitch, and consequent decision making) and kinesiological processes (position and movement during the swing – what coaches refer to as "batting mechanics" and "handling the bat"). The strategy to be used depends on such factors as the, number of outs, runners on base, score, count, coaches' signals and the speed, location and outcome of the previous pitch (Aaron and Cohen, 1974; Lau and Glossbrenner, 1984). The

batters mental model will be different if he foul tipped the previous pitch or blasted it over the fence, but just foul.

For a given set of situational factors, the batter uses heuristics to help select a specific implementation of a strategy (Schmidt and Ellis, 1994). With zero or one strike, the batter would "Predict the Pitch," whereas with two strikes the batter would "Protect the Plate." Within the "Predict the Pitch" strategy, the batter uses heuristics to help with the prediction. For example, with a count of 3 and 0 the batter would expect a fastball, whereas with a 0 and 1 count the batter might look for a curveball (Williams and Underwood, 1982). If the previous pitch were a ball, the batter is more likely to expect a fastball, whereas if the previous pitch were a strike, he is more likely to predict a breaking pitch, e.g., a curve or a changeup (Gray, 2003). The basis of these heuristics is the assumption that, when a strike is needed, most pitchers have the greatest confidence in the fastball.

The batter's set of cognitive processes includes a speed estimation process (shown in Fig. 10.4) that could be modeled with a Markov process or a Kalman filter. The present pitch speed is estimated using a weighted average of the last one or possibly two pitches (Bahill and Karnavas, 1993: Gray, 2002). Pitchers believe that the batter's memory span is 20 seconds. The speed estimator probably also uses information gathered in the first third of the pitch. It is not known how this process interacts with the above strategies and heuristics to help the batter predict when and where the ball will cross the plate.

10.8.2   Tactics of the Pitcher Versus Batter Confrontation

The battle of pitcher versus batter is the heart of baseball. In this contest, each participant employs a time-tested tactic: the batter uses mental models of the pitcher's previous pitches in order to anticipate the kind and location of the next pitch and the pitcher attempts to vary his pitches in order to fool the batter.

The pitcher's maneuvers are based on two assumptions. First, the movement, speed and location of a pitch will influence the batter's predictive model for the following pitch. For example, a high, inside fastball sets up the batter for a slow curveball, low and outside, because the batter cannot help but remember and adjust, at least in some small way, to the speed and location of the preceding fastball.

The second assumption of the pitcher is that, with respect to preventing the batter from hitting the ball well, vertical movement of the pitch is more effective than horizontal movement. The sweet region of the bat (the best part of the barrel for hitting the ball) is perhaps four inches long or longer (Seaver and Lowenfish, 1984; Williams and Underwood, 1982) but its depth

(along the transverse axis) is less than an inch. Consequently, the batter's margin of error is much smaller along the transverse axis compared with the longitudinal axis.

When the bat is swung at pitches that are mid-thigh high or higher, the longitudinal axis of the bat is almost horizontal as it passes through the strike zone. On a pitch that is knee high and on the outside corner, the angle of the bat with the horizontal plane is about ten to fifteen degrees, and this angle increases to about thirty or forty degrees on pitches that are knee high on the inside corner. For most pitches, then, vertical movement of the ball nearly parallels the transverse axis of the bat and increases the likelihood that the sweet region of the bat will pass over or under the center of the ball.

Given these assumptions, the pitcher's tactic is to select a pitch that will be different from the batter's predictive model and to provide adequate vertical movement of the ball to take advantage of the batter's vulnerability. The most important factor in pitch selection is the change of speeds. As a manager, Ted Williams exhorted his pitchers to never let a batter see consecutive pitches of the same speed. The great pitching coach, Johnny Sain, expressed the same maxim. In following this advice, pitchers exaggerate the speed differences between the overhand fastballs and the breaking pitches, thereby increasing the perceived vertical movement of the ball.

Some of baseball's fastest pitchers, such as Nolan Ryan and Rich Gossage, have used three speeds of their fastball to "go up the ladder" against the batter. This technique consists of throwing three high fastballs to a batter, each pitch faster and a little higher than the last. The batter experiences a jump on each pitch because of the speed differential. By the third pitch, the batter is swinging at an explosive fastball that is several inches out of the strike zone. The pitchers vary the speeds in this series because they recognize that this confutes the batter's predictive models, but few pitchers (if any) realize that this variation of speeds is inducing the perceptual illusion of the rising fastball.

The reverse technique, "going down the ladder," can be used on breaking pitches. Camilo Pascual had a legendary overhand curve that appeared to dive straight down just before it reached the plate. He would throw it at three speeds, enticing the batter to swing at progressively lower pitches. On one occasion, the batter actually broke his bat on home plate in trying to follow Pascual's curve.

We can describe other examples of slower speeds enhancing the illusion of the break on curveballs and on sinkers. Pitchers are advised by coaches to avoid throwing the curveball too hard (Ryan and House, 1991; Stanley and Stanley, 1988). The rationale usually given for this is that the slower curve has more time to "bite" the air - consequently, it will have a sharper break.

Relief pitchers who rely on sinkers are sometimes surprised that they are at their best when they are tired from pitching on several consecutive days. They lose some speed on their pitches and the sinker dips much more than it does when they are rested and strong (Thorn, 1979). Dusty Baker calls the sinker the toughest pitch to hit and has recommended that the batter study box scores in newspapers to determine a sinkerball pitcher's fatigue level (Baker, *et al.,* 1993).

The batter's antidote for the rising fastball and breaking pitches is to predict the next pitch and rehearse it with a mental simulation. This allows the batter to adjust expectations of the speed of the pitch. The batter can take measures to minimize the effects of the break or rise. If a breaking pitch is expected, the batter moves forward in the batter's box to "catch the ball before it breaks." Sievers (1958) and Gwynn and Rosenthal (1992) stress that the batter must concentrate on waiting as long as possible before committing the swing. If a high fastball is expected, the batter moves to the back of the box and prepares to swing at the upper half of the ball. With the count at less than two strikes, the batter has the luxury of taking the pitch if his prediction is wrong. With two strikes, the batter protects the strike zone by choking up on the bat and concentrating on hitting the ball up the middle (Baker, *et al.,* 1993).

Both pitchers and batters assume that the methods of grip and delivery a pitcher uses can make the pitches change course abruptly. Pitchers know that the speed of the pitch is important to its success, but they are unaware that success is dependent upon an illusion experienced by the batter. And the batters, too, do not realize that they are being fooled by their own expectations.

10.9 SUMMARY

One by one, scientists and engineers, using principles of physics, have explained most of baseball's peculiar pitches: e.g., the knuckle ball (Watts and Sawyer, 1975: Hollenberg, 1986), the scuff ball (Watts and Bahill, 2000) and the curveball (Watts and Bahill, 2000). The most mysterious remaining pitches were the rising fastball and the breaking pitches. Now, adding principles of physiological psychology, we can suggest that the rising fastball and the breaking pitches may be perceptual illusions, caused by the batter misestimating the speed of the pitch. Pitchers take advantage of these illusions when devising tactics and techniques but are generally unaware of the cause of these phenomena. However, Christy Mathewson (quoted by

Kahn, 2000) once said, "Fooling the other fellow was just as valuable as throwing hard – and a darn sight easier on the arm."

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10.11 BIOGRAPHICAL SKETCHES

Terry Bahill has been a Professor of Systems Engineering at the University of Arizona in Tucson since 1984. He received his Ph.D. in electrical engineering and computer science from the University of California, Berkeley, in 1975. He holds U.S. patent number 5,118,102 for the Bat Chooser, a system that computes the Ideal Bat Weight for individual baseball and softball batters. He is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE) and of INCOSE. He is chair of the INCOSE Fellows Selection Committee. His picture is in the Baseball Hall of Fame's exhibition "Baseball As America."

Dave Baldwin, as a relief pitcher for the Washington Senators, Milwaukee Brewers and Chicago White Sox during the 1960s and 1970s, compiled a lifetime ERA of 3.08 with 6 wins, 11 loses and 22 saves in 176 games. Following a 16-year baseball career, he earned a Ph.D. in genetics and an M.S. in systems engineering from the University of Arizona. Currently, he is an information and decision analyst for the HylaPark, Inc. in Carlsbad, CA. He is also a member of the Society for American Baseball Research (SABR).