The rising fastball: baseball's impossible pitch

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Abstract. Batters in professional baseball are confronted with pitches that appear to curve, dip, wobble, or rise. The rising fastball is a pitch where the ball appears to hop up as much as a third of a meter with a sudden increase in speed. Physics experiments confirm that many reported trajectories are possible, but not the rising fastball. The present paper shows how the apparent rise may be explained as a perceptual illusion due to the hitter underestimating original speed of the pitch.

1 Aerodynamics

Almost two hundred years before the advent of modern baseball, Isaac Newton (1671, 1809) described the aerodynamics of a curveball. Newton explained that spinning tennis balls curve because the spin leads to unequal air pressure on opposite sides of the ball. Other physicists reached the same conclusion not long after baseball began (Bache 1904; Brown 1913; Magnus 1853; Rayleigh 1877).

While Newton's explanation is elegant, it cannot account for many of the pitch trajectories described by baseball players (Allen 1982; Fimrite 1986). It does not explain how a knuckleball can wobble and change direction. It does not explain how a slider can start out straight and begin to curve near the end of the trajectory. And it does not explain how a rising fastball can accelerate upward with a hop just before it crosses the plate. Until recently, it was not clear whether such pitch trajectories were illusions or whether the physics model was inadequate (Drury 1953; Verwiebe 1942). After all, similar aerodynamic analyses had 'proven' that bumblebees cannot fly (McMasters 1989; Pringle 1957).

In the last thirty years, work done with balls in wind tunnels has confirmed that many erratic trajectories are possible. The aerodynamics of a hardball traveling at speeds up to 45 m s^{-1} (100 miles h^{-1}) is more complicated than the simple pressure differentials described by Newton and the other early physicists. Lateral curvature seems to occur only when the ball is traveling within a particular range of speed and spin rate where air boundary layers separate into an unbalanced turbulence pattern. The dynamics of the turbulence pattern are a function of two factors. First, ball spin provides a pressure differential known as Magnus force (Briggs 1959; Magnus 1853). Second, there is a range of velocity where drag conditions change dramatically, referred to as the region of 'drag crises' (Frohlich 1984, 1985). Together, the Magnus force and drag crises produce curvature within a range of velocity that is a function of size, mass, and surface roughness of the ball, as well as rate of spin (Bearman and Harvey 1976; Briggs 1959; Erlichson 1985; Frohlich 1984; Rex 1985; Watts and Baroni 1989; Watts and Ferrer 1986).

Wind tunnel tests demonstrate that balls with the proper speed and lateral spin rate can maintain turbulence conditions that lead to constant curvature throughout the trajectory of the pitch (Briggs 1959; Frohlich 1984; Watts and Ferrer 1986). These tests and photographic evidence confirm that a curveball can deviate from a straight path by as much as 0.4 m (Briggs 1959; Selin 1959; Watts and Ferrer 1986). Pitches can also be thrown with a speed and spin rate that allow the ball to enter or leave the region of curvature (Frohlich 1984; Hollenberg 1987; McLeod 1987). One example is the slider, a pitch that begins straight and then curves near the end of the trajectory (Allen 1982; Fimrite 1986). Thrown a little faster than a curveball, a slider will initially travel slightly above the speed where unbalanced turbulence occurs. Near the end of the trajectory the ball slows, the turbulence pattern begins, and the path curves (Frohlich 1984; McLeod 1987). A second example is a knuckleball, a pitch thrown with practically no spin that can change directions one or more times on its way to the plate (Watts and Sawyer 1975). Wind tunnel tests demonstrate that multiple direction changes can occur if the ball travels at the right speed and rotates about half a revolution over the distance to the plate (Frohlich 1984; Hollenberg 1987; Watts and Sawyer 1975). Under these conditions, change in seam position can greatly influence trajectory direction. The current aerodynamic theory is that the ball can enter and leave the region of unbalanced turbulence multiple times during the trajectory, and that direction changes may occur during each transition (Frohlich 1984; Hollenberg 1987).

Drag conditions influence not only lateral curvature of the ball, but height and speed as well. The travel time for a pitch to reach the plate ranges from about 0.4 to 0.8 s (Frohlich 1984; Selin 1959; Verwiebe 1942; Williams and Underwood 1986). During this time, the ball will drop 0.8 to 3 m owing to gravity alone. Consequently, all pitches start out either level or at a slight angle upward (Frohlich 1984; Selin 1959; Williams and Underwood 1986). If the ball is thrown with topspin, as is the splitfinger fastball, it will drop more (Fimrite 1986). If it has backspin, it will drop less (Brancazio 1984; Frohlich 1984; Rex 1985; Selin 1959; Verwiebe 1942; Watts and Baroni 1989). Though backspin can offset the effect of gravity, there is no scientific evidence that a ball can ever accelerate or rise above the starting angle of the trajectory. When the ball crosses the plate, the downward angle of the trajectory is always greater than when it left the pitcher's hand. Drag conditions influence height only by increasing or decreasing rate of fall and fall time (Frohlich 1984; Selin 1959).

Thus, aerodynamic theory leaves one pitch unexplained, the rising fastball. The rising fastball is a pitch which appears to accelerate upward with a hop just before it crosses the plate (Allen 1982; Fimrite 1986; Frohlich 1984; Selin 1959; Verwiebe 1942). Major league batters report rising fastballs that hop up as much as a third of a meter (1 foot), typically when the pitcher "put a little something extra on it" (Butler 1989). Practically all of the erratic pitch trajectories that baseball players claim to experience have been shown to be genuine, but physicists think the apparent rise must reflect some kind of illusion (Frohlich 1984; Selin 1959).

2 The hardest single act in all of sports

Perceptual studies of batting a baseball span at least fifty years (Portal and Romano 1988; Winograd 1942). A number of experiments demonstrate that it is impossible to track a pitched ball all the way to the plate (Bahill and LaRitz 1984; Hubbard and Seng 1954; Shank and Hayward 1987). In addition, the reaction time to swing a bat comprises a considerable portion of the time it takes a pitch to reach the plate (Messier and Owen 1984; Shank and Hayward 1987; Slater-Hammel and Stumpner 1950). If one further considers that the goal of the batter is to solidly hit the ball with the 'sweet spot' of a bat that is about three inches in diameter and to direct the ball away from fielders, it is not surprising that even the best major league hitters reach base only about a third of the time. This meager rate of success has led some authors to declare hitting a baseball "the hardest single act in all of sports" (Bahill and LaRitz 1984; Kindel 1983; Williams and Underwood 1986).

During the first few hundred milliseconds after a pitch is released, a good hitter must decide whether or not to swing the bat and where to locate the swing (Hubbard and Seng 1954; Messier and Owen 1984; Shank and Hayward 1987; Williams and Underwood 1986). Even the best of hitters can only continuously track the ball until it is a few meters from the plate (Bahill and LaRitz 1984; Hubbard and Seng 1954). On some at bats, a batter will make an anticipatory saccade, and divert his eyes to the planned point of contact above home plate (Bahill and LaRitz 1984; Ripoll and Fleurance 1988). While batters such as former Boston Red Sox great Ted Williams deny the popular claim that they actually see the bat hit the ball, they confirm that they see location of the ball as it crosses the plate to within about a centimeter (1/2 inch) (Williams and Underwood 1986). Thus, though the batter cannot continuously track the ball as it approaches, he can clearly perceive vertical location when it reaches the plate.

Considerable effort has been devoted to examining ability to judge time of arrival of the ball in both batting and catching tasks. Many studies confirm that batting and catching performance is correlated with length of sighting time (Alderson et al 1974; DeLucia and Cochran 1985; Diggles et al 1987; Fischman and Schneider 1985; Nessler 1973; Rosengren et al 1988; Sharp and Whiting 1974, 1975; Smyth 1986; Smyth and Marriott 1982; Whiting 1970, 1986; Whiting et al 1970). Prediction of ball destination seems to be continually updated throughout the trajectory of a pitch. The two primary cues used to judge time of arrival of an approaching ball are rate of optical expansion and rate of binocular convergence (von Hofsten 1987; Lee 1976; Lee et al 1983; McLeod et al 1985; Regan et al 1979; Todd 1981). Both of these cues exhibit slower rates of change when the approaching ball is farther away. This helps explain why batters can experience difficulty initially judging velocity of a pitch. Viewers often err in judgments of starting velocity (Runeson 1974, 1975). Thus, though the batter is relatively accurate in judging location of the ball as it crosses the plate, he can experience difficulty in judging distance to the ball as it approaches.

When baseballs are artifically propelled at relatively slow speeds, batters can hit the ball with remarkable consistency (McLeod et al 1985). In contrast, when initial distance and velocity of an approaching object are in the range of baseball pitches, viewers often err in judgments of arrival time (Harvey and Michon 1974; Schiff and Detwiler 1979). Studies that compare types of catching errors find both temporal and spatial errors at all levels of catching ability (Fischman and Schneider 1985; Savelsbergh and Whiting 1988; Whiting et al 1988). When the range of pitch variation is considered, it is impressive that batters make so few errors in judging location and time of arrival of the ball.

When the pitch nears the end of its trajectory, ball velocity exceeds the batter's tracking ability, and the experienced movement becomes a form of apparent motion. Internalized rules of apparent motion dictate that experienced movement will be continuous in time and space (McBeath and Shepard 1989). Thus, if a batter errs in his early assessment of location of the ball, the experienced trajectory may appear distorted later on, but will remain smooth. In order to make contact, the batter must formulate an accurate model of the trajectory and destination of the ball (Alderson et al 1974; Bahill and LaRitz 1984; Hubbard and Seng 1954; McLeod 1987; Ripoll and Fleurance 1988). Some pitches like the knuckleball and the 'change up' are intentionally thrown slowly, in the range of 20 to 30 m s^{-1} (45 to 70 miles h^{-1}) (Frohlich 1984; Selin 1959). When a pitcher throws these pitches he tries to trick the batter into swinging too early. Other pitches like the fastball, which has a velocity in the range 30 to 45 m s^{-1} (70 to 100 miles h^{-1}), may trick the batter into swinging too late. In either case, actual pitch velocity may differ from the batter's model of pitch velocity.

3 Explaining the impossible pitch

Error in the batter's model may account for the perceived rise of the rising fastball. One type of error that may be influential is underestimation in height of destination of the ball. Since backspin on some fastballs counteracts the fall of gravity, these pitches drop less than a normal falling trajectory. If humans have internalized the expected gravitational acceleration, anything that falls less could be construed to be rising. Still, it is difficult to conceive why the prototype of levelness should be an imaginary trajectory that falls at the rate of gravity rather than a simple horizontal plane. A more sensible interpretation when an object falls more slowly than expected is that it floats downward or 'hangs' in the air. In any case, the explanation of an underestimation in height fails to account for why the rising fastball seems to accelerate up with a hop.

The proposed explanation is that the perceived rise is primarily due to the batter underestimating initial speed of the pitch. If the batter maintains correct line of sight on the ball during the beginning and middle portions of its trajectory, a speed underestimation will cause the ball to appear both slightly farther away and slightly lower than its actual location. This is shown in figure 1 where the slower trajectory must drop more to maintain the same line of sight progression. During the initial and middle portions of the pitch, the experienced trajectory can remain relatively consistent with actual slower pitches. When the ball crosses the plate and the batter perceives its actual location, the experienced trajectory will be adjusted. Because the ball arrives a few milliseconds early and as much as a third of a meter above the anticipated arrival point, it will appear to hop up. This percept corresponds with descriptions given by major league hitters (Butler 1989). In formulating a continuous movement that connects initial and final perceived locations of the ball, the batter experiences the 'impossible' rising fastball.

The magnitude of perceived rise can be calculated with the use of estimates of experienced and actual velocities. The fall distance or drop due to gravity is a function of gravitational acceleration ($a = 9.8\ \mathrm{m\ s^{-2}}$), travel distance to the plate

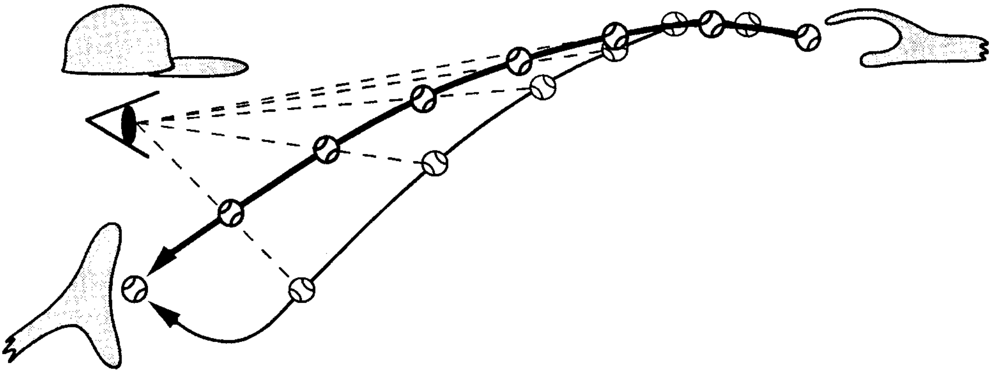

Figure 1. The illusion of the rising fastball. Top trajectory indicates actual path of a fastball. Bottom trajectory indicates path experienced by a batter who underestimates initial speed of the pitch. Dotted lines show line of sight to the ball at equal temporal intervals. Since distance to the ball is ambiguous, the line of site progression is consistent with both actual and experienced trajectories. If correct line of site is maintained, the slower, experienced trajectory will also appear lower. When the ball reaches home plate, its correct location can be accurately perceived. Therefore, near the end of the experienced trajectory, the ball will appear to accelerate up with a hop.

($d \approx$ 18 m from the pitcher's hand), and velocity of pitch (v):

$$\text{Drop} = \tfrac{1}{2}a\left(\frac{d}{v}\right)^2 = \tfrac{1}{2}(9.8\ \text{m s}^{-2})\left(\frac{18\ \text{m}}{\text{velocity}}\right)^2 .$$

If a fastball is experienced to move at a typical velocity of 37 m s^{-1} (83 miles h^{-1}), but is actually moving faster at 42 m s^{-1} (94 miles h^{-1}), the calculation is as follows:

$$\text{Experienced drop} = \tfrac{1}{2}(9.8\ \text{m s}^{-2})\left(\frac{18\ \text{m}}{37\ \text{m s}^{-1}}\right)^2 = 1.2\ \text{m}.$$

$$\text{Actual drop} = \tfrac{1}{2}(9.8\ \text{m s}^{-2})\left(\frac{18\ \text{m}}{42\ \text{m s}^{-1}}\right)^2 = 0.9\ \text{m}.$$

Hence experienced rise = (1.2 m)−(0.9 m) = 0.3 m. Thus the range of magnitude of rise due to underestimation of velocity matches reported range quite well. At fastball speeds, the perceived rise is about 5 cm for each m s^{-1} of speed underestimation (about 1 inch for each mile h^{-1} of speed underestimation).

4 Discussion

A number of empirical tests could be performed to confirm the proposed explanation of the rising fastball. First, the explanation makes vantage point a critical factor. For example, from the pitcher's vantage point, when initial velocity is underestimated the line of sight progression should also appear to accelerate. Yet, in contrast to the view of the batter, the ball should appear to level off with little if any rise. An observer who is off to the side, such as the first base coach, should also experience a much smaller rise if any. An observer well above and behind the pitcher should not experience a rise. This pattern is consistent with the lack of a dramatic rise observed when viewing from the vantage of television cameras off to the side or behind the pitcher (Selin 1959). It is also consistent with reports of catchers and first basemen that balls thrown to them can appear to hop up. Still, a more scientific test could be performed. A second test would examine if there is a correlation between pitch velocity and experienced magnitude of rise. Such a correlation is claimed by players, but has not been tested empirically (Butler 1989).

The proposed explanation requires that a batter does not adjust his model to account for faster pitches. In fact, it remains unclear how easy it is to make that adjustment. The task of judging location of a pitched baseball is at the limit of our perceptual abilities. Models used to enhance such judgments incorporate a combination of perceptual information and internal rules that may not be easily amendable to conscious control. Even if the model can be adjusted, any change should be evaluated in terms of overall success in judging location of the ball. A batter with a model that assumes faster pitches might misjudge more slow pitches and perform worse overall. A model which maximizes successful judgment of ball location should assume a velocity somewhere well within the distribution of pitch speeds. As a consequence, velocities on the tails of the distribution will continue to be misjudged. Therefore, even if a batter 'cues' on the average velocity of a particular pitcher's fastball, there may always be a few pitches thrown a little faster than usual, and these will appear to rise.

If batters misjudge location of some fastballs because of pitch variance, it follows that misjudgments also occur with other types of pitches. For example, the speed of slower pitches should sometimes be overestimated, making the ball appear to drop more than the actual trajectory. If the speed of a curveball is overestimated, it could also appear to curve more than the actual trajectory. The extent of such misperceptions is typically difficult to measure because both actual and experienced trajectories terminate at arbitrary downward and oblique angles. The unique characteristic of the rising fastball is that the perceived deviation crosses a salient demarcation, the horizontal plane. Perceptual error can therefore be more easily verified with the rising fastball.

If a speed underestimation leads to the apparent hop of acceleration, the same illusion ought to occur with other examples of quickly approaching objects. One corroborative example is the case when an automobile approaches and passes an observer. As with an approaching fastball, observers often experience a car to be moving relatively slowly when it approaches and to accelerate when it drives past. Viewers consistently err when judging arrival time of an approaching car (Schiff and Detwiler 1979). Similar distortions may occur whenever human processing limits are surpassed by an object moving across the visual field.

5 Summary

Since the time when Newton first described a curveball, our understanding of the aerodynamics of a baseball has advanced substantially. Wind tunnel and photographic tests confirm that pitched baseballs can curve, wobble, and dip, but that they cannot rise above the starting angle of the trajectory. Though backspin can counteract the influence of gravity, it cannot overcome it. The rising fastball has remained an unexplained pitch.

Perceptual studies document that though a batter can accurately locate the ball when it reaches him, he can experience difficulty perceiving distance to the ball while it approaches. To perform successfully, an internal model of the trajectory must be formulated. The present paper shows that when a batter underestimates initial speed of a fastball, it may appear lower during the middle portion of the trajectory, and then seem to accelerate upward with a hop as it crosses the plate. The rising fastball, the last of the unexplained pitches, appears to be a perceptual illusion.

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