Tie Goes to the Runner: The Physics and Psychology of a Close Play

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Tie Goes to the Runner: The Physics and Psychology of a Close Play

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Since physics is often a service course for college students, it is important to incorporate everyday examples in the curriculum that inspire students of diverse backgrounds and interests.[1-5] In this regard, baseball has been a workhorse for the physics classroom for a long time, taking the form of demonstrations and example problems. Here, we discuss how baseball can help bridge the physical and social sciences in an introductory physics course by analyzing a close play at first base.

In the realm of the physical sciences, David Kagan has published a number of "physics of baseball" results appropriate for the introductory physics classroom. In particular, he has shown the best launch angle to hit a home run,[6] modeled the drag on a ball using free Major League Baseball (MLB) data,[7] and even described the kinematics of a stolen base[8] and the physics of replay reviews.[9]

Luckily, physicists are not the only ones interested in baseball as a platform to understand the world. In psychology, researchers have found that vision training can improve batter performance,[10,11] outfielders fail to estimate the apex of a ball's trajectory,[12] and referees (known as umpires in baseball) show bias toward pitchers of similar race.[13] So, for those students who are interested in the social or medical sciences but are required to take physics as part of their training, is there a way to use the canonical sport of baseball to blend physics and psychology principles in an introductory course?

Let us first set the stage for our science experiment. A player (the "baserunner") strikes the baseball with his bat, sending it into the field. As the ball flies, the baserunner charges toward first base as shown in Fig. 1. The defenders collect the ball and throw it toward the first baseman, who catches it in a glove. If the ball arrives at the glove before the baserunner tags first base with his foot, then the baserunner is called "out" by the umpire.

Due to their constant and essential involvement in the game, umpires have historically played a pivotal role in baseball. In particular, we are interested here in how well an umpire can determine if a baserunner is safe or out while running through first base. Note that many baseball fans believe the rules state that a tie goes to the runner; however, this is *not* the case (formally or in practice).

First, we will assume that the umpire stands at some significant distance d away from first base. Second, we will assume that at this distance, the umpire is incapable of watching both the ball as it impacts the glove of the first baseman and the foot of the baserunner as he approaches first base. From this assumption, we arrive at the standard method by which an umpire is trained to call a close play at first base:

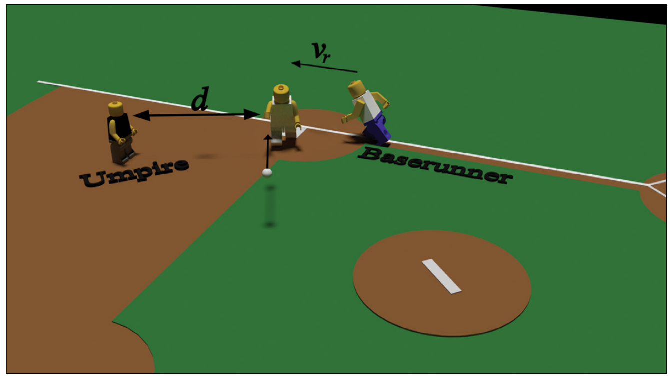

Fig. 1. A close play at first base involves a fast-moving baserunner, a fast-moving ball, and an umpire attempting to determine the order of two events.

> **The umpire *watches* the foot of the baserunner and *listens* for the ball as it impacts the glove.**

From this information, we can now evaluate the basic physics of how the umpire experiences a close play at first base.

The physics approach

Anyone familiar with a fireworks display already knows that the speed of light and the speed of sound are not the same. In fact, the speed of light is so fast that only 54 μs pass while light from fireworks travel to you from 10 miles away. In contrast, the sound from those same fireworks takes 47 s! For this reason, we can treat the speed of light as infinite (and therefore the light arrives instantaneously).

With this in mind, we must remember that the umpire is using two *different* types of signals (sound and light) to measure two events (ball hits glove and foot hits bag). First, we tabulate values used in our analysis, shown in Table I. We list the speed of light in vacuum (in m/s) along with the index of refraction of air at room temperature. From this, we can calculate the speed of light as $v_l = c/n$. The speed of sound is calculated (in m/s) as $v_s = 331.4 + 0.6T$, with T measured in degrees Celsius. The separation between the umpire and first base d is calculated from images of a MLB game.

Table I. Important assumptions for time calculations.

speed of sound	v_s	344.6 m/s
speed of light	c	299,792,458 m/s
index of refraction	n	1.000293
temperature	T	22.0 °C
separation	d	6.62 m

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With these values at hand, we can easily calculate the time it takes for a signal to travel via light or sound respectively from first base to the umpire: $T_l = d/(c/n) = 22.1$ ns, $T_s = d/v_s = 19.2$ ms. Noting that 6.62 m is about 22 ft, we see that light travels about 1 ns for every foot of distance. The relative delay for *simultaneous events* (a tie at first base) is $\Delta T = T_s - T_l \approx T_s = 19.2$ ms.

This may not seem like such a long time for most human experiences, but how important is it in a baseball game? To answer that, let us think about how fast a MLB baserunner might be moving as he approaches first base. Luckily, David Kagan considered the kinematics of a particularly fast baserunner (Carl Crawford) attempting to steal second base. He found that Mr. Crawford attained a maximum speed of approximately $v_r = 8.56$ m/s, long before he reached second base. We can therefore assume that a speedy baserunner might obtain this same speed while traveling to first base.

Using this speed, an obvious question is, "How far does Mr. Crawford move in 19.2 ms?" In this case, we find $d_C = v_r \Delta T = 16.4$ cm or about 6.47 in! Let us call this the Crawford distance. Anyone familiar with baseball should be astounded by such a large number. To clarify this result, let us consider three possible scenarios.

- ***Scenario 1 (near perfect tie):*** The baserunner arrives at the bag *at the same moment* the ball impacts the glove (within measurement precision).

In this scenario, the umpire will hear the ball hitting the glove 19.2 ms after he sees the foot of the baserunner arrive at the bag. He calls the baserunner safe. In fact, if the baserunner arrives at first base before the ball arrives, the umpire will always get the call correct. This seems to reinforce the old adage: Tie goes to the runner.

- ***Scenario 2 (actually out):*** The ball strikes the glove while the baserunner is 16.5 cm away from first base, slightly larger than the Crawford distance.

In this scenario, the sound from the ball arrives at the umpire's ear after 19.2 ms have passed. Meanwhile, the baserunner has been closing the gap on the base, taking $T = 0.165/v_r = 19.3$ ms since the ball arrived. For a perfect umpire, he would hear the ball 0.1 ms before seeing the baserunner's foot hit the bag. The umpire correctly calls the runner out. So far, the umpire is doing a stellar job.

- ***Scenario 3 (actually out):*** The ball strikes the glove while the baserunner is still 16.3 cm away from first base, but slightly under the Crawford distance.

In this scenario, the sound still takes 19.2 ms to reach the umpire's ear. However, before the sound arrives, the baserunner has closed the gap (in 19.0 ms) and that signal travels nearly instantaneously to the umpire. The umpire incorrectly calls the baserunner *safe*.

Based purely on the speed of the two signals, and assuming that the umpire can detect auditory and visual signals *perfectly* as they arrive, a baserunner can be "out" by up to 16.3 cm and still be called safe. Therefore, the Crawford distance is the distance by which a baserunner can be "out" and still be called "safe."

Another consideration a student might explore is the effect of temperature or air pressure. For instance, the hottest baseball game on record (1988, Texas vs. Toronto) was 109 °F (42.8 °C), and the coldest game (2013, Colorado vs. Atlanta) was 23 °F (-5 °C). This changes the speed of sound, and alters the Crawford distance to 15.9 cm (hot) and 17.3 cm (cold).

The psychology approach

While the physics approach clearly demonstrates that an umpire should fail in scenario three listed above, we have neglected to account for the umpire's profound disability: he is human.

Before getting into any details about how the umpire being human would influence this situation, it is important to understand how psychology can help us. Although the layperson's first thought when hearing the word psychology is often "Freud," psychology is much more than dream analysis and people reclining on couches. Two subfields in psychology are particularly relevant to this question. The first, psychophysics, explores the relationship between physical stimuli in the world (such as the motion of a baseball into a glove) and our sensation and perception of that stimulus (i.e., our actual psychological experience of the event). The second, neuropsychology, examines how the entire range of psychological experiences (from emotion to learning to behavior) relate back to what is actually happening in the brain. These two approaches can provide us with the context we need to explore the umpire's behavior.

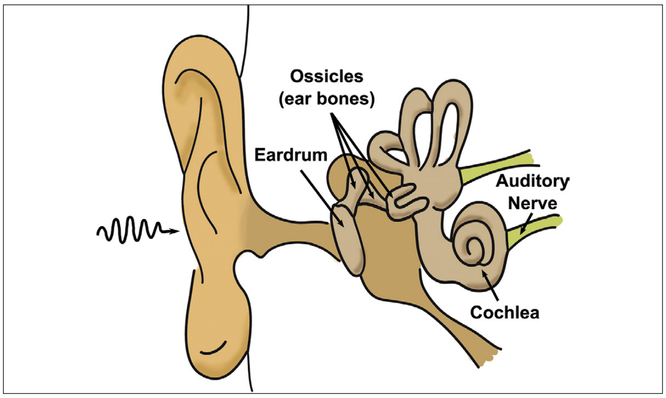

Fig. 2. The sound of a ball hitting the first baseman's glove coming into the ear.

Because the umpire is a fallible human being, it is not enough to just consider the time difference at which the auditory and visual signals reach the umpire's ears and eyes, respectively. Instead we need to also take into account what the human mind does with these types of inputs. Our interpretation of stimuli is not immediate, but instead relies on a complex biological and psychological system, similar to the electronic rise-time of a detector.

Let us consider a *very simplified* explanation of audition, as shown in Fig. 2. First, pressure waves travel into the ear and strike the eardrum. These vibrations are then converted into mechanical motion (movement of small bones called ossicles), followed by pressure waves in fluid residing in the cochlea. This fluid motion disturbs tiny hair cells, generating electrical and chemical signals. These signals are transmitted via the auditory nerve from the cochlea to the brain for interpretation. For this reason, although this process is fast enough that we are unaware of any delay, it does take time for these signals to propagate through our auditory system and then be interpreted by the brain.

In contrast to the sound and light delays described by physics, neural processing time is much faster for *auditory stimuli* (approximately 10 ms) than for visual stimuli (approximately 50 ms).[14] Therefore some of the discrepancy that we would expect the umpire to experience (because of the faster transmission of light than sound) is mitigated. As a result of these different speeds of neural transmission, psychologists have coined the term "horizon of simultaneity" for the distance range of 10-15 m. In this range, any differences in the physical speed of sound and light in the environment is canceled by neural processing time,[15] given by a straightforward kinematic analysis. Note that this range is larger than the typical distance of the umpire from first base.

The "horizon of simultaneity" would be a simple answer to the umpire's problem if it were not for the fact that humans are not perfect detectors. In addition to this neural processing time, humans do not simply experience auditory and visual stimuli—we also need to *interpret* them. Numerous studies have demonstrated that we make errors when determining when auditory and visual signals occur at the same time. In these studies, a light and sound source are mounted together at a variable distance from an observer. When placed one meter away, we perceive the light and sound as happening simultaneously if the light is turned on first. But with more distance from the observer, we are more likely to perceive them as simultaneous if the sound is played before the light is illuminated.[16] This makes sense from an evolutionary perspective as we have evolved in a universe in which sound travels more slowly than light. We have a built-in bias that may be attempting to partially compensate for this difference.

Levitin and colleagues[17] compared the sensitivity threshold for determining auditory-visual simultaneity in both an actor (e.g., a baserunner) and an observer (e.g., an umpire). Participants heard the sound of a drum stick hitting a drum pad through headphones. The sound was triggered by a computer at a range of offsets from when the drum stick actually made contact. One participant hit the drum pad while blindfolded (giving them auditory and tactile information) while the other participant watched the event at a distance (auditory and visual information). Both participants listened to the sound (sometimes shifted in time) over headphones. Their task was to say whether or not each sound/hit pair occurred simultaneously. It was determined that while the actor detected asynchrony when the sound was at least 25 ms early or 42 ms late, the observer (at 2 m distant) was only able to do so when the sound was 41 ms early or 45 ms late.[17] This suggests that the first baseman or runner, who are physically involved in the event, actually have a stricter threshold for accepting simultaneity than the umpire!

Conclusions

We have found that if we consider only the physics of a close call, an umpire will preferentially call a fast baserunner safe even if he is out by the Crawford distance of 16 cm. However, this conclusion fails to account for how sight and sound are processed by the human mind. Taking into account the delay experienced by an umpire for the two stimuli, he should stand farther away from the play (approximately 10 m) in order to see and hear simultaneous events as simultaneous[14] (otherwise, a tie will go to the *defense*). However, even with this new placement, it is unclear if humans, due to their innate biases, are even able to detect asynchrony if the two events are off by up to 40 ms in either direction.[17] (This corresponds to a Crawford distance of 1 ft!)

So how do umpires perform so well under such difficult conditions? One reason may be that they have extensive experience viewing these types of events, and there is strong evidence that vision training can improve performance in sports.[10,11] Additionally, it is likely that MLB umpires have self-selected based upon their innate abilities where only the most perceptive make it to the top level of umpiring.

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And the Survey Says ...

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First- and multi-career physics teachers

In our 2012-13 Nationwide Survey of High School Physics Teachers, we asked whether teaching high school was the respondent's first career. More than 40% of the respondents indicated that teaching high school was *not* their first career. We call this group multi-career teachers. The table reveals differences and similarities for first- and multi-career teachers.

First- and Multi-Career Teachers
2012-13 Nationwide Survey of High School Physics Teachers

	First-Career	Multi-Career
Median age*	42 years	50 years
Median years teaching*	15 years	10 years
Has a major in physics or physics education*	35%	27%
Has a major *or minor* in physics or physics education*	45%	35%
AAPT member*	20%	29%
Bachelor's is highest earned degree	37%	29%
Doctorate is highest earned degree*	2%	10%

* indicates that these differences are statistically significant

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There are several statistically significant differences between first-career and multi-career teachers. Not surprisingly, first-career teachers are younger and have more teaching experience than multi-career teachers. Perhaps counterintuitively, even though a higher proportion of first-career teachers have a major in physics or physics education, a higher proportion of multi-career teachers are members of AAPT. While about one-third of teachers in both groups have a bachelor's as their highest earned degree, multi-career teachers are more likely to have a doctorate than first-career teachers.

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