Dear Phundayers,

I wrote this paper initially for a history of science seminar. But since then, I've been a tad confused about where to take it.

I have tried to make the case that the increasing use of computer-vision based Automatic Line Calling (ALC) systems in tennis, rather than other kinds of systems, is closely tied to the fact that these systems are able to make their workings visible through visualizations. They are thus able to appeal to our special sense of sight. In the paper, I tried to show this by closely analyzing the visualization that Hawk-Eye uses, as well as showing its changes in time. Finally I pointed to new visualizations that TV stations are able to build using the data collected by Hawk-Eye as evidence for its "center of calculation" status.

Do these claims seem tenable? Does the analysis of the visualizations make sense? What kinds of journals could I publish this analysis? And what kinds of literature could I put this into conversation with? What kinds of changes would I have to make and what kinds of new evidence would I have to marshal in order to be published?

Any help, suggestions, etc. would be most appreciated! Thank you,
Shreeharsh

The Power of Sight: The Case of Hawk-Eye in Tennis

At 6-2, 4-6, and trailing by 4-5, and with the score poised tantalizingly at 40-40 in what proved to be the final game of her quarter-final match with Jennifer Capriati in the 2004 U. S. Open, Serena Williams hit an inside-out forehand deep to Capriati's backhand. Capriati scrambled to retrieve it and landed a floating ball almost smack in the center of the court, which Williams promptly dispatched with a nicely angled forehand cross-court. Alas, for Williams, the ball, which seemed to be on the line, was called out. Williams exclaimed and shook her head in disbelief. Three calls in that final set had gone against her, shots she believed were all winners, one of them, in particular, an egregious over-rule where the ball had bounced well inside the side-line. Capriati had a match-point. Williams lost the match on the next point[1].

[1] To see the four contested calls, see (Anon. 2011) To see the New York Times report on the match, see (Brown 2004) For the most egregious call in the match, a case of multiple rules being broken at the same time, see (Anon. 2008)

Unbeknownst to her, Williams had an ally. A computer vision system called *Shot Spot* had been installed on the court: it tracked the ball as it flew around the court and plotted the exact impact point where the ball hit the court. It then turned its data into a visualization that showed the computed trajectory of the ball, zooming in to show the "mark" that the ball made when it landed on the court.

The system's output was however only available to television stations. Unlike slow-motion replays in which commentators strain to figure out whether the ball was in or out, *Shot Spot* showed them to see what it "saw" computationally – in beautifully drawn straight lines and curves. Williams' forehand was on the line. "Gimme a break," said John McEnroe, no stranger to arguing with chair umpires himself. "This is ridiculous," he continued, his voice dripping with disgust.

McEnroe's frustration must have communicated itself to the public and to the United States Tennis Association (USTA). Mariana Alves, the chair umpire, was removed from officiating any further matches at the Open that year and the USTA made a formal apology to Williams. The incident is widely credited with being a major reason for the introduction of Automatic Line Calling (ALC) systems into tennis.

In August (just before the Williams-Capriati fracas) and again in the November of 2004, the Canadian Auto-Ref system had been tested and cleared by the International Tennis Federation (ITF) using the guidelines that the ITF had set up in 2003. Hawk-Eye, a British system made by Hawk-Eye Innovations Inc., was tested in December 2004. Both systems were deemed to show "sufficient promise." [2]

[2] The ITF's press releases on each of these trials are available at this URL: http://www.itftennis.com/technical/news/newsarticle.asp?articleid=13003. The evaluation protocol can be downloaded here: http://www.itftennis.com/shared/medialibrary/pdf/original/IO_5918_original.pdf.

Of the two, it was Hawk-Eye that was first used at a Grand Slam: the 2006 US Open. (Each player was allowed to challenge two calls per set.) It was used in the Australian Open in 2007 and at Wimbledon the same year. By March 2008, the three governing bodies in tennis, the ITF, the ATP and the WTA had standardized the rules for using Hawk-Eye: each player is now allowed to make a maximum of three incorrect challenges per set and an extra challenge if the set reaches a tie-breaker (Anon.). Till today, the French Open remains the only Grand Slam which does not use Hawk-Eye. Since the French Open is played on clay, the ball leaves a mark and the mark can be checked if the call is disputed. However Hawk-Eye is still installed on show-courts and does get used by TV stations to replay close-call points (Martin 2009).

Collins and Evans (2008; 2011) have analyzed the Hawk-Eye system for its claims of accuracy. They point out, reasonably enough, that the visualization – the output of the system – hides several choices that are made in order to produce it. Most importantly, they criticize the system for hiding its probabilistic calculations; the visualization, with its neat straight lines and perfect curves, hides the messiness of the actual court as well as the fact that its calculations have a margin of accuracy. They recommend that the visualization must reflect the error probabilities inherent in the calculation.

In this paper, I will concentrate on Hawk-Eye as a *business* artifact, and on the new ways in which it ties together disparate actors. I propose to analyze two aspects of Hawk-Eye. First, I will compare Hawk-Eye to other ALC systems and argue that the adoption of a certain kind of system over others, while justified mainly in terms of its technical superiority, becomes possible when the system becomes a "center of calculation" that holds together an entire ecology, in this case, the worlds of tennis, television and their publics. I will also argue that this becomes possible because Hawk-Eye can demonstrate its credibility – through its visualization – in a way that other competing systems could not and did not.

Sources of credibility

Let's look at the other ALC systems. My source for this is the proceedings of the Tennis Science and Technology conference organized in 2003 by the International Tennis Federation, where five papers were presented on ALC systems (Fisher 2003; Szirmak and Harmath 2003; Carlton and Carlton 2003; Jonkhoff 2003; Marshall 2003). Curiously, Hawk-Eye does not appear anywhere in this conference, although its competitor Auto-Ref does. In addition, a search on Google Patents reveals many other kinds of electronic systems for line calling[3]. Rather than summarizing each system, I will classify them based on the kinds of methods they employ.

Beam systems: Beam systems like Cyclops (the earliest ALC system, first installed at Wimbledon in 1980 and at the Australian and US Opens subsequently) work by throwing electromagnetic beams from one side of the court to another. The beams are carefully positioned: for Cyclops, one beam is on the service line (parallel to the baseline); the other four beams are outside the line i.e. in the "out" area. By carefully calculating which beams were interrupted, these systems can decide if the ball was in or out. If the ball is out, Cyclops produces a beeping sound (Carlton and Carlton 2003).

Wired systems: Wired systems wire up the lines on the court and perhaps also the balls themselves. I call them "wired" systems because they require going into the innards of physical entities like balls and tennis courts. Tennis Electronic Lines (TEL) is an early electronic system built by a Dutch company. In TEL, the balls as well as the

[3] Go to http://www.google.com/patents and search for "tennis line call" to get a list of granted and applied-for patents related to this theme.

lines are equipped with electronic sensors. The lines can "sense" the ball when it is close and an algorithm then calculates the "footprint" of the ball. The algorithm tries to take into account the compressibility (i.e. whether the ball is elongated or squished which should therefore affect its footprint) and whether the ball is skidding. TEL was tried at the US Open in 1992 on all the non-service lines. They found that out that in 9% of all close calls, the umpires and TEL arrived at different results (Jonkhoff 2003).

A patented system developed by Signal Processing Systems Inc. (SPS) in Sudbury, MA, embeds electronic sensors into the court lines. These sensors generate signals when the line is "touched" by a ball. These signals are turned into sounds which are piped to the line umpires manning that particular line. The line umpires will then use their judgment: they will augment their visual survey of the line with the sound produced by the system in order to call a ball in or out (Fisher 2003)[4].

Computer vision systems: The last type of ALC systems uses computer vision to calculate the ball-impact position. In basic terms, this means using cameras positioned at different points on the court to calculate the 3-d trajectory of the ball's flight after it leaves the racquet.

Auto-Ref and Hawk-Eye are standard computer vision-based systems. Both systems deploy a number of high-speed cameras around the court, keeping track of the cameras' relative positions with respect to each other. The image extracted from each camera is processed to obtain the two-dimensional coordinates of the ball and the court lines in the image. The 2-d positions and the relative positions of the cameras are used to compute a 3-dimensional model of the ball's trajectory with respect to the court lines. This, in turn, is used to compute the "foot-print" of the ball on the court, taking into

[4] For other examples of beam and wired systems see (Levey 2001).

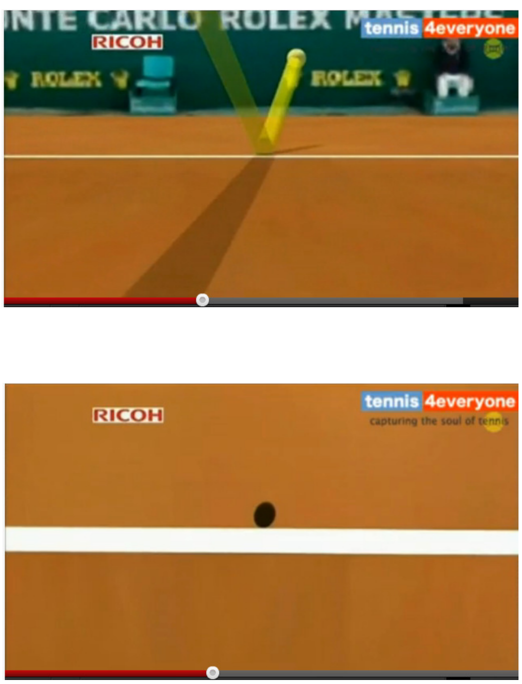
consideration the velocity and the estimated compressibility of the ball. Finally, the 3-d trajectory is used as input to a visualization algorithm that is then shown to the audience as well as the umpire.

The first key difference between these three types of systems is that computer vision systems are “review” systems (“designed to provide a replay as an aid for the Chair Umpire”) while beam and wired systems are “real-time” systems (“i.e. designed to make line calls immediately”) (ITF Technical Centre 2010). There are some obvious advantages to computer vision systems. First, they don't require digging up the court to install sensors or to wire up the balls although they do need to be installed and calibrated. Second, they need only be brought into play when a call is challenged, and they are more immune to false positives: thus, there's no question of beeping when a player steps on the line which can all-too-easily happen for wired or beam systems.

In a 2007 paper, Jamie Capel-Davis and Stuart Miller of the ITF lay out the "general principles" for an ALC system to be "acceptable." According to them, a system should be: “accurate,” “reliable,” “practical,” and “suitable.” Here “practical” means "easy to use" by chair umpires in a way that does not interfere with their other duties and "suitable" means that the system is useful in all the possible conditions that exist in a tennis match (rain, wind, etc.) and that it not expose players to health risks (Miller and Capel-Davies 2007, 388). Can we point to any of these four factors as unequivocal reasons for the eventual success of computer vision systems?

I will argue that one key reason for their success today is that these systems offer more "credibility" than the others. At the same time, they function as powerful "centers of calculation” (Latour 1988) that link and hold together the intertwined worlds of tennis and television, and their associated publics, in a way that the other systems cannot.

First, the credibility. Steven Shapin (1995) points out that in opposition to the traditional understanding of science which assumes that scientific claims are credible because they are valid, science studies takes as its starting point the idea that scientific claims *become* valid because they make themselves more credible to their audiences (who may be scientific or other kinds of publics). This credibility is produced by using different techniques of persuasion (graphs, charts, equations, diagrams, experiments) that are suitable for the public being addressed, which is itself being disciplined to see things a certain way. The success of Hawk-Eye (as the exemplar of computer vision systems) can be seen to come from its production of credibility, its ability to persuade different publics. Let's see how.



Video from http://www.youtube.com/watch?v=Cgeb61VIKvo

Figure 1: The figure at the top shows a still from a Hawk-Eye animation. Notice that the color of the court is brown since the match is being played on a clay court in Monte Carlo. Notice that the visualization has a "memory" and shows the trajectory of the ball as a tunnel-like structure. Notice also the back of the court which is closely modeled on an actual court complete with a seated line umpire and the name of the tournament. The figure at the bottom shows a "top view' of the mark made by the ball on the court. Hawk-Eye thus allows its viewers to become referees who can inspect the mark made by the ball on the court, just like actual umpires.

The important difference between the three types of systems is this: beam systems and wired systems analyze what happens at the point of impact. These systems do not trace the ball as it arrives at its point of point of impact, nor do they have to, in order to produce a result. Computer vision systems however need to trace the trajectory of the ball in order to determine the point of impact. The ability to compute and visualize a trajectory allows computer vision systems to make their audiences *see* their working in what one might call a "transparent" way. (Beam and wired systems often produce their output as a sound: a beep. It seems harder for them to translate their working into a visual for audiences to see.) As Richard Wright (2008, 79) points out, "visualizations are created for people rather than machines." And of all our senses, sight is considered to be the most context-independent, culture free, transparent, and the most persuasive (Rorty 1979, 38–39). Although as Charles Goodwin shows in his brilliant deconstruction of the Rodney King trial, publics must be trained to "see" in order to persuade them (Goodwin 1994; Wright 2008, 82).

Wright (2008, 79) continues: "A visualization is distinguished by its algorithmic dependence on its source data and its perceptual independence from it." How does the Hawk-Eye visualization secure its "perceptual independence" from its source data and hence, presumably, its persuasive power? First, the visualization is mimetic; it is customized to the court the match takes place on. The visualization preserves the color (blue, green) and the texture (in a very basic sense, by visually distinguishing grass, carpet, and hard courts) of the court. It also places images of objects and people on the court: line umpires, clocks, service speed indicators, the name of the tournament, all of which make the simulated court look like a real one. Second, it holds on to the convention of making the screen a window into another world; telecasts of sports on television almost invariably do this. Third, the visualization borrows some visual conventions from computer games (e.g. tennis on the Wii): the neatly drawn straight lines, the almost perfect circular/elliptical shape of the ball, and a complete absence of texture (you wouldn't know that a tennis ball has fluff all over it, or that lines that make up tennis courts are painted and scruffy). In a sense, the visualization is of the form that Daston and Galison (2010) call “truth-to-nature.” Fourth, it makes the viewer himself into a camera. The viewer is able to fly along the court (similar to the way Second Life allows him to "teleport") and look at the moving ball from different angles; this viewer flight usually ends with him looking "down" at the "mark" made by the ball on the court, i.e. its impact point. The impact point itself is usually rendered without any messiness: it is very clear to the viewer if the ball is in or out. Finally, in a move that is drastically different from how we usually "see," the visualization has a memory: even as the ball is moving, the viewer can see all its previous positions since the trajectory of the ball is literally drawn using tunnel-like structures, as if the ball is creating a pipe as it moves. This final move might be the most important way in which the visualization demonstrates the working of the system, to convince its viewers. (See Figure 1 for an illustration).

The production of this kind of credibility is not available to other systems. Could they make themselves credible in other ways, or by not appealing to the sense of sight? Perhaps, but with the success of computer vision systems, it's hard to imagine credibility being produced in any other way.

My point about credibility will become clear by seeing the changes in the Hawk-Eye visualization since 2004. Over the years, the visualization has become: (a) even more mimetic, in terms of looking more and more like the court the match is played on, (b) longer, in terms of showing the trajectory of the ball, and (c) richer, in that it can now incorporate more views and angles and has memory. The visualization now allows the viewer to fly with the ball to see, looking down, the mark made by the ball on the court; in 2004, it merely allowed the viewer to see the line from the point of view of the line umpire policing the line. Over the same time, player complaints about the system have reduced (Pilhofer 2008). Today, it seems to be just another part of the tennis landscape. For more details on this, see Figure 2.

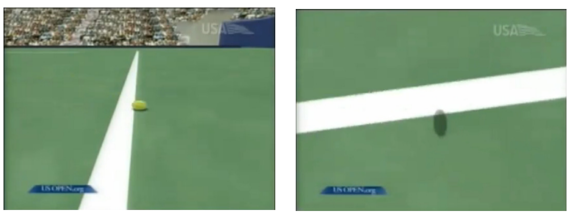


Figure 2: (a) shows the visualization circa 2004. The duration is roughly 5 seconds. The court is rendered in a less "mimetic" way. The visualization starts with a line umpire's view of the line and ends with a top-view of the "mark" made by the ball.

(a)

(b)

(b) shows the visualization circa 2009. The court is now considerably embellished with markers to make it look more "real." The visualization now lasts for much longer: roughly 10-12 seconds. Finally, the visualization, instead of putting the viewer in the position of the line umpire, seems to mimic the point of view of the ball. The viewer appears to fly along the court, as if following the ball. It ends with the viewer looking down at the mark made by the ball. Notice that the visualization allows the viewer to zoom in considerably more than before. Both visualizations (a) and (b) use clean lines, more "truth-to-nature" than real. (b) also shows the trajectory of the ball using a tunnel-like visual, which (a) does not.

Hawk-Eye as a "center of calculation"

The second reason for the eventual success of computer vision systems (exemplified by Hawk-Eye) is that it is more than an ALC system; it is an amazingly detailed system of surveillance that tracks the ball as it moves around the court, from its contact point with the racquet to its impact on the court. It records who won the point, and it records how the point was won (an ace, a winner, a forehand or backhand, or an unforced error).

Beam and wired systems cannot function as surveillance systems. These systems are too scattered and decentralized: sensors embedded in balls and lines, localized beams to monitor specific lines. To integrate these fragments into a complete panoptic record seems difficult, if not impossible. Computer vision systems, on the other hand, have an almost gods-eye vantage point to view the court. It's no wonder that they function so well as a link between the worlds of tennis and television. Perhaps, one might say, the reason for our very real preference for a system geared towards a production of mechanical objectivity rather than systems that produce objectivity as trained judgment is that mechanically objective systems (which have fewer points where humans intervene) are better at surveillance, and therefore, more productive. (Daston and Galison 2010).

Bruno Latour points out that one relationship between knowledge and power lies in the development of what he calls "centers of calculation." As I understand him, he is referring to systems that produce inscriptions (maps, equations and others) which then colonize different aspects of the world around them, piercing through previously impervious boundaries between activities (Latour 1988). Hawk-Eye can be seen to be a similar center of calculation. It produces inscriptions, numerical data that binds television stations and the world of tennis even closer. This data allows the production of a certain kind of "fairness" on the court and therefore appeals to certain publics (tennis fans and viewers, including television viewers). More importantly, it enables the formation of a competing center of authority: television viewers get the ability to see whether certain on-court decisions were right or wrong (irrespective of whether they were challenged on court).

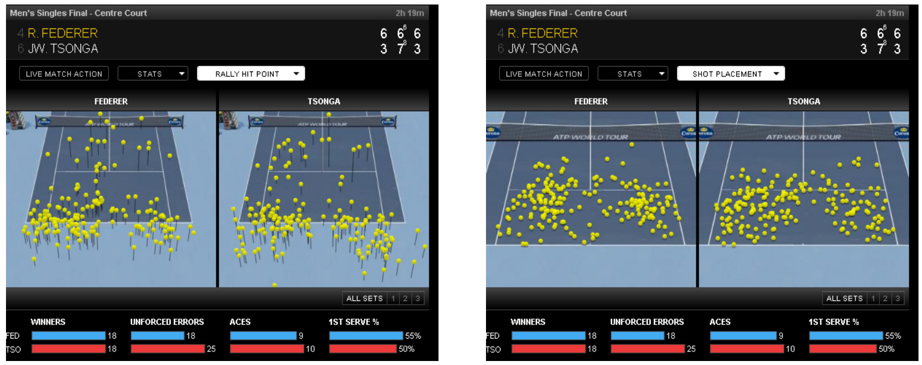


Figure 3: The figure on the right shows the contact points i.e. the point of contact of the ball with the player's racket. The figure on the right shows where the players hit the ball i.e. it shows the various impact points.

Finally it allows the production of even finer statistics and slick visualizations that television stations see as the source of their popularity with their publics. It gives them a means for attracting (or creating) newer publics who are interested in reaching out to each other through joint explorations of statistics. ESPN.com, for example, recently created a new website called CourtCast (Anon.). CourtCast allows its users to watch a match "live" through a simulated visualization (which is streamed real-time, and is a transformed version of Hawk-Eye data). It allows them various other options: to see a "rally" from different points around the court, to see statistics about aces, winners, forehands, backhands all visualized in terms of the ball-impact position on court as well as its contact-point with the racket. Users can also use the new social media, like Twitter, to talk to each other about these statistics. (See Figure 3 for some screenshots of CourtCast.)

Conclusion

This essay has purported to show that the success of a computer vision-driven Automatic Line Calling system should be seen less because of criteria like accuracy and reliability and more because these systems produce a kind of credibility (by demonstrating their working through visuals) that other systems cannot. They also function as "centers of calculation" tying together the diverse worlds of tennis, television, and their publics.

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