In or Out: The Politics of Hawk-Eye in the Game of 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 even well inside the side-line. Capriati had a match-point. Williams lost the match on the next point[1].

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. In addition to slow-motion replays in which commentators strain to figure out whether the ball was in or out, <u>Shot Spot</u> now allowed them to see what it "saw" computationally – the ball's trajectory after it left the racquet and the mark it made when it landed on the

[1] To see the four contested calls, see *Serena Williams vs Jennifer Capriati Blown Calls*, 2011, http://www.youtube.com/watch?v=F4mGqwA7cCM&feature=youtube_gdata_player. To see the New York Times report on the match, see Clifton Brown, "Umpire's Unforced Errors Help Lift Capriati," *The New York Times*, September 8, 2004, sec. Sports / Tennis, http://www.nytimes.com/2004/09/08/sports/tennis/08tennis.html?_r=1&ref=jennifercapriati. For the most egregious call in the match, a case of multiple rules being broken at the same time, see *Jennifer Capriati vs Serena Williams Us Open 2004*, 2008, http://www.dailymotion.com/video/x7fuj4_jennifer-capriati-vs-serena-william_sport.

court – all in beautifully drawn straight lines and curves. The ball, it turned out, was on the line. "Gimme a break," said John McEnroe, no stranger to arguing with chair umpires himself, his voice dripping with disgust. "This is ridiculous."

McEnroe's frustration must have communicated itself to the public and to the United States Tennis Association (USTA). Mariana Alves, the chair umpire for the Williams-Capriati match, was removed from officiating any further matches at the Open that year, and the USTA made a formal apology to Williams, especially for the call where a shot that did not even touch the line was called out. The incident is widely credited with being a major reason for the introduction of Automatic (or Electronic) 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, was tested in December 2004. Both systems were deemed to show "sufficient promise."

It was however Hawk-Eye, made by Hawk-Eye Innovations Inc. 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[2]. 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

[2] "Hawk-Eye," *Wikipedia, the free encyclopedia*, n.d., http://en.wikipedia.org/wiki/Hawk-Eye.

and the mark can be checked if the call is disputed. However Hawk-Eye is installed and is still used by TV stations to replay close-call points[3].

Collins and Evans have analyzed the Hawk-Eye system for its claims of accuracy. They point out, reasonably enough, that the visualization that gets generated by the Hawk-Eye system hides several choices that get made in order to produce the visualization. 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 of the calculation[4].

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 with 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 in a way that other competing systems could not and did not. Second, I will look at the ways in which Hawk-Eye collects data and the new ways of knowing that this gives rise to.

[3] John Martin, "Why No Hawk-Eye at Roland Garros?," *Straight Sets: Tennis Blog of the New York Times*, June 2, 2009, http://straightsets.blogs.nytimes.com/2009/06/02/why-no-hawk-eye-at-roland-garros/.

[4] H. Collins and R. Evans, "You cannot be serious! Public understanding of technology with special reference to 'Hawk-Eye'," *Public Understanding of Science* 17, no. 3 (2008): 283–308. See also H. Collins and R. Evans, "Sport-decision aids and the 'CSI-effect': why cricket uses Hawk-Eye well and tennis uses it badly," *Public Understanding of Science* (2011).

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[5]. 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[6].

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[7].

Beam systems have one main drawback. They are sensitive to the beams being interrupted by other objects, not just the tennis ball. Thus Cyclops was only deployed at

---

[5] J. Fisher, "A line calling system to improve line umpire performance," ed. Stuart Miller (presented at the Tennis Science and Technology 2, International Tennis Federation, 2003); P. Szirmak and M. Harmath, "Automated tennis line judging," ed. Stuart Miller (presented at the Tennis Science and Technology 2, International Tennis Federation, 2003); B Carlton and S Carlton, "Cyclops electronic service line calling system for tennis," ed. Stuart Miller (presented at the Tennis Science and Technology 2, International Tennis Federation, 2003); H. Jonkhoff, "Electronic line-calling using the TEL system," ed. Stuart Miller (presented at the Tennis Science and Technology 2, International Tennis Federation, 2003); J Marshall, "Theoretical comparison between single and multi-light beam semiautomatic line judging systems," ed. Stuart Miller (presented at the Tennis Science and Technology 2, International Tennis Federation, 2003).

[6] 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.

[7] Carlton and Carlton, "Cyclops electronic service line calling system for tennis."

the service line to evaluate serves (and needed to be switched off manually after the serve so that it did not beep during a point if the ball bounced on the service line). It would be much harder to use it on the baseline where players are stationed since their bodies would be constantly interrupting the beam.

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 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[8].

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[9].

[8] Jonkhoff, “Electronic line-calling using the TEL system.”
[9] Fisher, “A line calling system to improve line umpire performance.”

Wired systems seem to have similar drawbacks as beam systems: they are sensitive not just to the balls but also to bodies and other objects. Yet, these drawbacks are overcome in interesting ways in these two systems described above. TEL wires the ball as well as lines and thereby is able to avoid false positives when a player, say, steps on the line. SPS's system is still sensitive to other objects, but their system is not meant to deliver the final verdict on the point; rather, it is meant to provide additional information to the line umpires during close calls. To use the different kinds of objectivity that Galison and Daston bring out in their study of 19th century natural atlases, SPS's system understands its functions as a matter of supplementing “trained judgment” by humans, while all the other systems embody notions of mechanical objectivity[10].

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.

[10] Lorraine Daston and Peter Galison, *Objectivity* (Zone Books, 2010).

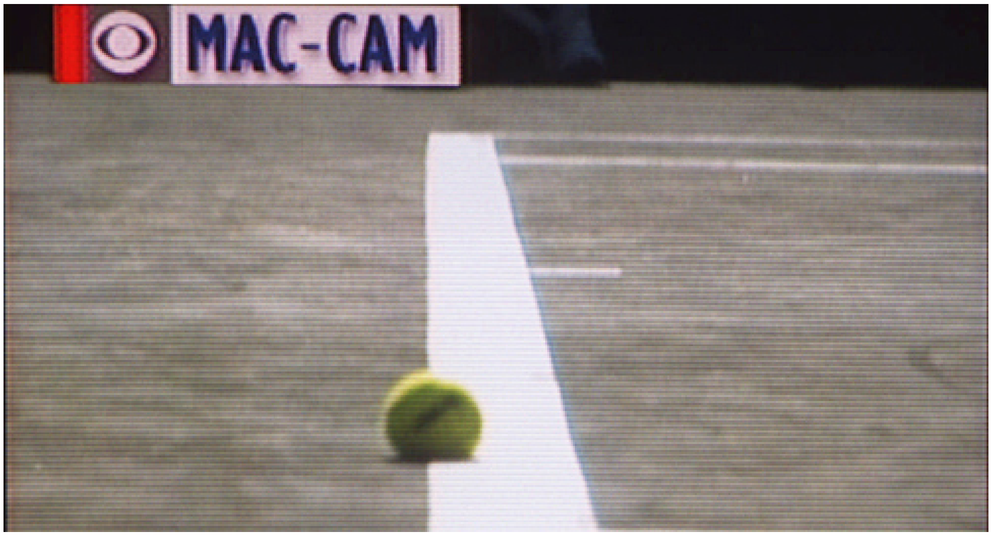

Figure 1: The startling clarity of a Mac Cam image.

Let's first consider the Mac Cam. This is not exactly a computer vision system since it performs no computations, and is just a sensor device, yet I include it here because it uses a camera, and it makes an interesting counter-point to actual computational vision systems like Auto-Ref and Hawk-Eye. Mac Cam was built by Del Imaging Systems[11] and was first used by CBS in 1996 at the US Open. Essentially high-speed cameras were placed at the baseline (to eliminate parallax), and take rapid snap-shots up to 5000 frames per second. By replaying the images captured by the camera on close calls, it is possible for humans to see if the ball is in or out. In addition, Mac Cam images allow users to see the compression and skid of the ball as well as figure out its actual point of contact with the ground[12].

[11] See http://www.delimaging.com/fastcamreplay.htm.

[12] Julie Cart, "'Mac Cam' Not the Future, Yet," *Los Angeles Times*, September 16, 1996, http://articles.latimes.com/1996-09-16/sports/sp-44568_1_mac-cam.

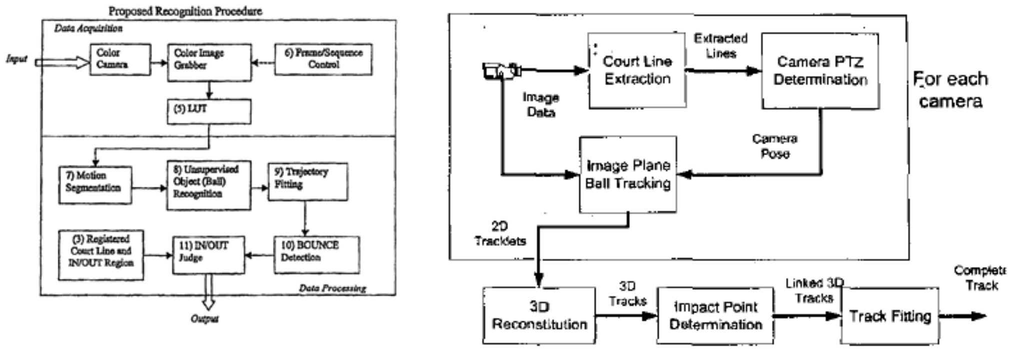

Figure 2: The flow-chart for Auto-Ref is on the left, for Hawk-Eye, on the right.

Auto-Ref and Hawk-Eye, which have already been referred to, are more standard computer vision-based systems. In Figure 2, I show a block-diagram of the system from Auto-Ref's (granted) patent[13] as well as a block-diagram from an opaque paper[14] published on Hawk-Eye[15].

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 positions (i.e. in the image) of the ball and the court lines. The positions in the previous image are used to "filter" for the positions in the subsequent image. The 2-d positions and the relative positions of the cameras are used to establish correspondences between the images and 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 consideration the velocity and the estimated compressibility of the ball. Finally, the 3-d trajectory is used

[13] Miki Harmath, “System and method for judging boundary lines”, November 9, 2004, http://www.google.com/patents?id=6ogRAAAAEBAJ.
[14] N. Owens, C. Harris, and C. Stennett, “Hawk-eye tennis system,” in *Visual Information Engineering, 2003. VIE 2003. International Conference on*, 2003, 182–185.
[15] The block diagrams are startlingly similar and perhaps speak to the folly of the idea of software patents themselves.

as input to a visualization algorithm that is then shown to the audience as well as the umpire.

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. Second, they need only be brought into play when required and they are more immune to false positives (for example, there's no question of beeping when a player steps on the line which can all-too-easily happen for wired or beam systems). Amongst the systems themselves, Mac Cam is a costly camera (450,000 dollars in 1996[16] but probably cheaper today), and would need to be deployed on every line. In contrast, Auto-Ref and Hawk-Eye seem less costly (20,000 dollars per week per court for Hawk-Eye, according to one source[17]) but they need skilled personnel to operate them.

It's worth stepping back at this point to understand why exactly computer vision systems (or rather, Hawk-Eye) have emerged the winners in this battle between systems. Technical discussions of this question are almost always about accuracy and error. Thus in the Tennis Science and Technology conference in 2007, Jamie Capel-Davis and Stuart Miller of the ITF lay out the "general principles" for a 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

[16] Cart, “‘Mac Cam’ Not the Future, Yet.”
[17] See http://blog.jasontsang.ca/2006/07/technology-in-tennis-hawk-eye.html.

possible conditions that exist in a tennis match (rain, wind, etc.) and that it not expose players to health risks[18].

Can we point to any of these four factors as unequivocal reasons for the eventual success of computer vision systems? Are computer vision systems inherently more accurate, reliable, practical and suitable? Certainly, one could make a case for them in terms of their practicality and suitability: computer vision systems require least work from chair and line umpires, and no digging up of the courts, while being more reliable than beam systems, and less prone to false positives.

Yet, I will argue that one key reason for their success today is that these systems offer more "credibility" than others. At the same time, they function as powerful "centers of calculation[19]" that link and hold together the intertwined worlds of tennis and television, and their associated publics, in a way that other systems cannot.

First, let's take the issue of credibility. Steven Shapin points out that an important point about science studies is that it takes the credibility and validity of scientific claims as separate but inter-related objects of study. Rather than 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 (which 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

[18] Stuart Miller and Jamie Capel-Davies, "Evaluation of automated line calling systems," ed. Stuart Miller and Jamie Capel-Davids (presented at the Tennis Science and Technology 3, International Tennis Federation, 2007), 388.
[19] Bruno Latour, "Visualisation and Cognition: Drawing Things Together," in *Knowledge and Society Studies in the Sociology of Culture Past and Present*, vol. 6 (Jai Press, 1988), 1-40, http://www.bruno-latour.fr/articles/article/21-DRAWING-THINGS-TOGETHER.pdf.

suitable for the public being addressed. Yet, it must also be remembered that persuading a public of a certain claim requires disciplining the public, to train the public to "see" things in a certain way[20]. 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.

The important difference in the three classes 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 a trajectory allows computer vision systems to demonstrate their working in what one might call a "transparent" way. (It's true that this demonstration requires visualization and it's also true that the visualization hides the actual choices made during the computation and makes the system feel more accurate than its actual working would indicate.) Computer vision systems can use the data they generate, the 3-d trajectory, to make their audiences *see* what they have computed, thereby making themselves transparent, in a way that is harder for other systems to do.

How does Hawk-Eye translate its output, the 3-d trajectory, into a visualization that demonstrates its credibility? As Richard Wright points out, "visualizations are created for people rather than machines[21]." Hawk-Eye itself does not need to visualize the ball to know if it is in or out, but its viewers need to in order to accept what the

---

[20] S. Shapin, "Cordelia's love: credibility and the social studies of science," *Perspectives on science* 3, no. 3 (1995): 255–275.
[21] Richard Wright, "Data Visualization," in *Software studies: a lexicon*, ed. M. Fuller (The MIT Press, 2008).

system is doing. 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. And of all our senses, "seeing" is considered the most context-independent, culture free, and transparent[22], the most persuasive. 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[23].

Figure 3: 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. 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.

Wright continues: "A visualization is distinguished by its algorithmic dependence on its source data and its perceptual independence from it.[24]" 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

[22] For the relationship between seeing, knowledge, ways of knowing, and certainty see R. Rorty, *Philosophy and the Mirror of Nature* (Princeton Univ Pr, 2009), 38–39.
[23] C. Goodwin, "Professional vision," *American anthropologist* 96, no. 3 (1994): 606–633. See also Wright, "Data Visualization," 62.
[24] Ibid., 60.

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, 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 (for 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). 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 3 for an illustration).

The production of such a 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.

Perhaps the only exception to this is the Mac Cam whose images have a startling and almost breathtakingly simple power to them (although, even here, considerable work has gone into this, starting from the way the camera is placed, as well as its frame-rate). As some tennis fans argue, Hawk-Eye's visualization is far too "cartoony" and is "estimated[25]." The Mac Cam's images, on the contrary, seem far more real. The Mac Cam can also show the ball moving (although not the complete trajectory, but at least in its field of vision). This provides it with one more resource to demonstrate its credibility. When then, do we see Hawk-Eye being used and not the Mac Cam? The answer may lie in Hawk-Eye's ability to function as a link between the worlds of television and tennis, and in its potentially transformative ability to collect data, a capability the Mac Cam does not have[26].

Hawk-Eye as a "center of calculation"

Hawk-Eye is not just an automatic line calling 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 and on and on until the point ends. 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).

Television stations connect the world of tennis to its diverse publics. These publics are all over the globe and they come together to watch tennis matches, sometimes assembling in person, at other times virtually (in forums like Talk Tennis), but mostly

[25] See, for example, this exchange in the Talk Tennis forums: http://tt.tennis-warehouse.com/showthread.php?t=287369.
[26] Cart, "'Mac Cam' Not the Future, Yet."

coming together through the shared experience of watching tennis matches on TV. Hawk-Eye, as we saw at the beginning of this essay, was first used by television stations to provide their publics with newer and better ways of seeing what was happening on court. Television stations have typically done this by providing statistics. With Hawk-Eye, they were able to demonstrate to their viewers the fairness or unfairness of the decisions being taken on the court. The Capriati-Williams match became a touchstone because television publics were persuaded that they knew what *really* happened and an injustice had been done to Serena Williams.

In the conclusion of his piece on visualization and cognition, Bruno Latour points out that the relationship between knowledge and power might be 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[27]. Thus the material-symbolic mélange called "Wall Street" can be seen as a center of calculation: by producing sophisticated financial instruments, many different activities were brought together: the housing market, the holdings of banks, and the sovereign debts of nations (through currency flows).

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:

[27] Latour, “Visualisation and Cognition.”

television viewers get the ability to see whether certain on-court decisions were right or wrong (irrespective of whether they were challenged on court).

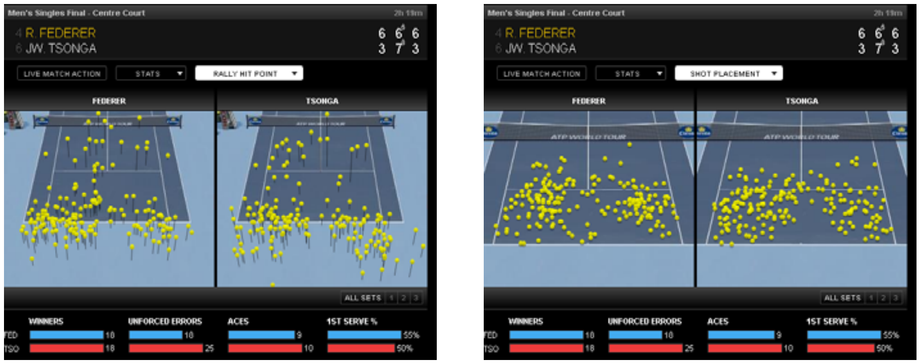

Figure 4: The figure on the right shows the contact points i.e. the point of contact of the ball with the player's racket. The figure on the right shows where the players hit the ball i.e. it shows the various impact points.

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[28]. 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 4 for some screenshots of CourtCast.)

[28] See http://scores.espn.go.com/sports/tennis/courtcast.

Finally, the data produced by Hawk-Eye has another public: tennis players themselves, who may use it as a resource for new ways of acting. Hawk-Eye data is owned by Hawk-Eye and is often given to players who "request" it. Thus an article in the Wall Street Journal tells us:

> All of this information is stored to be used in the future. To prepare his charge for a match with Rafael Nadal at Wimbledon in 2008, Andy Murray's coach requested the data on where the Spaniard had placed all of his serves in previous matches at the Championships in order to try and discern a pattern and hence give Mr. Murray a possible edge in their quarter-final encounter.
> What he learned was that Mr. Nadal had indeed changed his game plan for Wimbledon. On the clay at the French Open that year he hit the vast majority of both first and second serves to the backhand of his right-handed opponents. But on the lawns of the All England Club he sent far more serves at his opponent's forehand; his second serves were regularly fired at their bodies[29].

The collection of data can thus engender new ways of knowing. Sports such as tennis are often characterized as being only about "tacit knowledge[30]." Thus we have Jonah Lehrer, a science reporter who frequently writes on issues on neuroscience, in an article on tennis courts in *Grantland* magazine:

> As a result, players must always take the coefficient of friction into account, even if they don't know what the coefficient is. "The top-ranked guys are all intuitive physicists," Hofmann says. "They know how the ball will bounce even if they can't explain why. This is what allows them to change their strategy based on the surface[31]."

In this article, which is about the importance of tennis surfaces, and by implication the relevance of physical quantities like the coefficient of friction, angle of

[29] Jason Goodall, "Tennis Becomes a Numbers Game," *The Wall Street Journal*, July 5, 2010, http://online.wsj.com/article/SB10001424052748704103904575336984166968328.html.
[30] Michael Polanyi, *The Tacit Dimension*, Reissue. (University Of Chicago Press, 2009).
[31] Jonah Lehrer, "The Physics of Grass, Clay and Cement," *Grantland*, August 29, 2011, http://www.grantland.com/story/_/id/6906922/the-physics-grass-clay-cement.

bounce and rebound, and the coefficient of restitution to the playing of the game, Lehrer seems to be arguing that while playing tennis can often be "reduced[32]" to the laws of physics, tennis itself, the act of playing, is tacit knowledge in action. No propositional knowledge of the laws of physics helps, you just have to be an "intuitive physicist."

This makes the distinction between tacit and explicit knowledge far too stark and unbridgeable, as though the only way of bringing propositional knowledge of physics into the game is if the players start calculating in their heads. If knowledge of the game is considered as something that resides in a person's head or body, and then gets displayed on courts, then, yes, there's only tacit embodied knowledge. But if, channeling Edwin Hutchins[33], the world of tennis is considered to be a network then the propositional knowledge of physics comes into it at a number of different points:

Racket technology: There are actual physicists and material scientists who work on rackets. They design rackets that are designed for different types of playing styles[34] and different types of surfaces. This is propositional knowledge as encoded into artifacts (in this case, the tennis racket), which the players then use.

Coaching: Coaches help to get a lot of propositional knowledge on to the courts. What's a "good" service action? How much back-swing should you have while playing a stroke? Is a long back-swing bad for grass? A lot of this is backed up by actually thinking about physics and kinesiology and it gets incorporated into a player's game. Novak Djokovic recently improved his service by making a "minor" adjustment – but this

[32] A social scientist would remark that the word "reduce" seems to be doing a lot of work here.
[33] Edwin Hutchins, *Cognition in the Wild*, New edition. (The MIT Press, 1996).
[34] Christopher Clarey, “Wimbledon: For Nadal, Federer and Djokovic, Rackets Complete the Player,” *The New York Times*, June 19, 2011, sec. Sports / Tennis, http://www.nytimes.com/2011/06/20/sports/tennis/20iht-SRWIRACKET20.html.

may have been key to his recent success because he is able to get some free points on his serve (69 more aces, apparently)[35].

Playing strategy: Recordings of previous matches are now easily available and allows players and their coaches to construct what is called a game-plan. Game-plans are products of conscious reasoning and pattern recognition about an opponent's weaknesses and strengths – a combination of propositional knowledge and trained judgment. Of course, strategizing is, in Lucy Suchman's famous formulation[36], like planning how to take your canoe into the rapids: once you start playing and are thrown into the contingencies of a game, it just becomes one resource amongst many many others. But it is propositional knowledge, nevertheless, and is often the product of a whole network of people thinking: coaches, practice partners, managers, consultants, etc. as well as technologies like statistics, video recordings and such.

As the example above shows, Hawk-Eye can indeed be a resource for different kinds of strategy-making by players. It can show information that would not be accessible by watching videos of tennis matches. Just as data-collection and chess-playing programs have revolutionized the playing of chess[37], one might think that the collection of data might change the game of tennis too. My suspicion is that even if it does, it will be in a way different from chess. Chess is after all a sport that is uniquely susceptible to algorithmic analysis. It has no time-limit on how long players may think (except in speed chess). Tennis is faster and far more embodied. Yet the use of data-

[35] Greg Bishop, "For Top-Ranked Djokovic, Next Makeover Is in Marketing," *The New York Times*, August 25, 2011, sec. Sports / Tennis, http://www.nytimes.com/2011/08/26/sports/tennis/next-makeover-for-djokovic-a-new-no-1-is-in-marketing.html.

[36] Lucy A. Suchman, *Plans and Situated Actions: The Problem of Human-Machine Communication*, 2nd ed. (Cambridge University Press, 1987), 52.

[37] R.R. Desjarlais, *Counterplay: An Anthropologist at the Chessboard* (Univ of California Pr, 2011).

analysis in tennis can perhaps be a gateway for a sociologist who wishes to study the connections between tacit and explicit knowledge.

Conclusion

This brings me to my last point with which I want to conclude this essay. Hawk-Eye's website has a long advertising document on how the system (which is largely the kinds of data and visualizations that it produces) may be useful in coaching tennis players. The system is called the Hawk Eye Tennis Coaching System[38]. The slightly strained and needy language used in the document makes me think that Hawk-Eye hasn't yet found a way to sell this system as much as it had hoped. Yet, the system is interesting in its own right. Established tennis players can use Hawk-Eye data to strategize. One might think: if statistics were just not just to strategize but to produce and constitute tennis players beginning from their fledgling years, how might the game of tennis change?

Bibliography

Bishop, Greg. "For Top-Ranked Djokovic, Next Makeover Is in Marketing." *The New York Times*, August 25, 2011, sec. Sports / Tennis. http://www.nytimes.com/2011/08/26/sports/tennis/next-makeover-for-djokovic-a-new-no-1-is-in-marketing.html.

Brown, Clifton. "Umpire's Unforced Errors Help Lift Capriati." *The New York Times*, September 8, 2004, sec. Sports / Tennis. http://www.nytimes.com/2004/09/08/sports/tennis/08tennis.html?_r=1&ref=jennifercapriati.

Carlton, B, and S Carlton. "Cyclops electronic service line calling system for tennis." edited by Stuart Miller. International Tennis Federation, 2003.

Cart, Julie. "'Mac Cam' Not the Future, Yet." *Los Angeles Times*, September 16, 1996. http://articles.latimes.com/1996-09-16/sports/sp-44568_1_mac-cam.

Clarey, Christopher. "Wimbledon: For Nadal, Federer and Djokovic, Rackets Complete the Player." *The New York Times*, June 19, 2011, sec. Sports / Tennis. http://www.nytimes.com/2011/06/20/sports/tennis/20iht-SRWIRACKET20.html.

[38] You can read the document here: http://www.hawkeyeinnovations.co.uk/UserFiles/File/Hawk-EyeCoaching_Public.pdf.

Collins, H., and R. Evans. “Sport-decision aids and the ‘CSI-effect’: why cricket uses Hawk-Eye well and tennis uses it badly.” *Public Understanding of Science* (2011).

———. “You cannot be serious! Public understanding of technology with special reference to ‘Hawk-Eye’.” *Public Understanding of Science* 17, no. 3 (2008): 283–308.

Daston, Lorraine, and Peter Galison. *Objectivity*. Zone Books, 2010.

Desjarlais, R.R. *Counterplay: An Anthropologist at the Chessboard*. Univ of California Pr, 2011.

Fisher, J. “A line calling system to improve line umpire performance.” edited by Stuart Miller. International Tennis Federation, 2003.

Goodall, Jason. “Tennis Becomes a Numbers Game.” *The Wall Street Journal*, July 5, 2010. http://online.wsj.com/article/SB10001424052748704103904575336984166968328.html.

Goodwin, C. “Professional vision.” *American anthropologist* 96, no. 3 (1994): 606–633.

Harmath, Miki. “System and method for judging boundary lines”, November 9, 2004. http://www.google.com/patents?id=6ogRAAAAEBAJ.

“Hawk-Eye.” *Wikipedia, the free encyclopedia*, n.d. http://en.wikipedia.org/wiki/Hawk-Eye.

Hutchins, Edwin. *Cognition in the Wild*. New edition. The MIT Press, 1996.

Jennifer Capriati vs Serena Williams Us Open 2004, 2008. http://www.dailymotion.com/video/x7fuj4_jennifer-capriati-vs-serena-william_sport.

Jonkhoff, H. “Electronic line-calling using the TEL system.” edited by Stuart Miller. International Tennis Federation, 2003.

Latour, Bruno. “Visualisation and Cognition: Drawing Things Together.” In *Knowledge and Society Studies in the Sociology of Culture Past and Present*, 6:1-40. Jai Press, 1988. http://www.bruno-latour.fr/articles/article/21-DRAWING-THINGS-TOGETHER.pdf.

Lehrer, Jonah. “The Physics of Grass, Clay and Cement.” *Grantland*, August 29, 2011. http://www.grantland.com/story/_/id/6906922/the-physics-grass-clay-cement.

Marshall, J. “Theoretical comparison between single and multi-light beam semiautomatic line judging systems.” edited by Stuart Miller. International Tennis Federation, 2003.

Martin, John. “Why No Hawk-Eye at Roland Garros?” *Straight Sets: Tennis Blog of the New York Times*, June 2, 2009. http://straightsets.blogs.nytimes.com/2009/06/02/why-no-hawk-eye-at-roland-garros/.

Miller, Stuart, and Jamie Capel-Davies. “Evaluation of automated line calling systems.” edited by Stuart Miller and Jamie Capel-Davids. International Tennis Federation, 2007.

Owens, N., C. Harris, and C. Stennett. “Hawk-eye tennis system.” In *Visual Information Engineering, 2003. VIE 2003. International Conference on*, 182–185, 2003.

Polanyi, Michael. *The Tacit Dimension*. Reissue. University Of Chicago Press, 2009.

Rorty, R. *Philosophy and the Mirror of Nature*. Princeton Univ Pr, 2009.

Serena Williams vs Jennifer Capriati Blown Calls, 2011. http://www.youtube.com/watch?v=F4mGqwA7cCM&feature=youtube_gdata_player.

Shapin, S. "Cordelia's love: credibility and the social studies of science." *Perspectives on science* 3, no. 3 (1995): 255–275.

Suchman, Lucy A. *Plans and Situated Actions: The Problem of Human-Machine Communication*. 2nd ed. Cambridge University Press, 1987.

Szirmak, P., and M. Harmath. "Automated tennis line judging." edited by Stuart Miller. International Tennis Federation, 2003.

Wright, Richard. "Data Visualization." In *Software studies: a lexicon*, edited by M. Fuller. The MIT Press, 2008.