Adjudication in Cricket

Borooah, Vani

Ulster University

October 2023

Chapter 5
Adjudication in Cricket

5.1 Introduction

Play in a cricket match is adjudicated by two umpires — one at the bowler's end, the other at square-leg. When a bowler has completed their over, and before a new over (with a different bowler) begins from the opposite end, the umpires switch positions — the square-leg umpire moves to the bowler's end and the bowler's end umpire goes to square-leg. The position of these umpires in the context of the fielding positions in cricket is shown in Figure 5.1, below. All appeals by the fielding side claiming that, for a myriad reasons, one of the batters is 'out' and must return to the pavilion making way for a new batter, are addressed to these umpires who either uphold the appeal by raising their finger or reject it with a shake of the head, usually accompanied by a firm call of 'not out'.[1] The umpires' decision is final and, indeed, a hallowed cricketing convention is for players to accept the decision, however much they might disagree with it, without demur and certainly without visible dissent.

In informal games, the batting side supplies as umpires two persons from their team who, while they are officiating, are supposed to suspend their team loyalties, with the side that is currently fielding reciprocating when it comes to their turn to bat. In more formal matches, it is the responsibility of the home team to supply two umpires who are not part of either team and whose impartiality, if only for that reason, is not in doubt.

Leg-before-wicket (lbw) is the most contentious of the major forms of dismissal, invoking the greatest degree of subjectivity from the umpires (see box below on the lbw rule). Even though, in contests between countries, umpires in Test Matches were more prone to give visiting batters out lbw- than home batters, the system of 'home country' umpires continued as long as their bias was not too blatant.[2] The catalyst for change was provided by an infamous incident in Faisalabad, Pakistan, on 1

[1] A batter can be 'out' in ten possible ways: bowled; leg-before-wicket (lbw); caught; stumped; run out; hit wicket; handling the ball; hitting the ball twice; obstructing the field; and, when the new batsman takes too long to appear, 'timed out'. Of these, the first five are the most common with the last four occurring very rarely.

[2] For every decade up to the 1990s, lbw made up a greater proportion of dismissals of away, compared to home, batters (Leamon and Jones, 2021, chapter 5).

December 1987 when the Pakistani umpire, Shakoor Rana, was confronted over an on-field incident, while play was in progress, by the English touring captain, Mike Gatting. The result was that after a great deal of finger-wagging and exchange of hard words between captain and umpire, a day's play was lost.[3] As Anglo-Pakistani relations reached a new low, the British Foreign Office became involved and, to repair the situation, Gatting was forced to apologise.[4]

Box 5.1: The lbw Rule

The batter is adjudged to be lbw if a *legally delivered* ball would have gone on to hit the wicket but for the fact that it struck a part of the batter's body (except the hands holding the bat).

So, to uphold an appeal for lbw, an umpire must judge three things: (1) Where was the ball pitched? A batter cannot be given out lbw to a ball pitching outside the leg stump. (2) Did the ball strike the batsman in line with the stumps? Provided a batter was playing a shot, they cannot be given out lbw to a ball making contact outside the off stump. (They can, however, be given out lbw to a ball striking them outside the off stump if the umpire believed that they were not playing a shot.). (3) Would the ball have gone on to hit the stumps? A batter cannot be given out lbw to a ball which, in the opinion of the umpire, would have missed the stumps.

So, in response to an lbw appeal, umpires will raise their finger if, and only if, they believed all three conditions were satisfied: (i) the ball did not pitch outside the leg stump; (ii) it made contact in line with the stumps; (iii) it would have gone on to hit the wicket.

Umpires will declare the batter to be not out if any of conditions (1)–(3) was not met. Umpires will be particularly concerned with whether the ball hit the bat *before*, or *after*, striking the body. In the first case, the batter is not out; in the second case, the batter is *eligible* to be given out lbw.

[3] The incident itself was trivial. With Eddie Hemmings bowling, Gatting brought David Capel in from deep square-leg to prevent a single. According to the captain, he had informed the batsman, Saleem Malik, of this but Rana, standing at square-leg, stopped play and accused Gatting of cheating. https://www.cricketcountry.com/articles/the-infamous-mike-gatting-shakoor-rana-altercation-20634 (accessed on 21 July 2021).

[4] The apology could not have been more perfunctory: 'Dear Shakoor Rana, I apologise for the bad language used during the 2nd day of the Test match at Fisalabad (sic). Mike Gatting, 11th Dec 1987'. See previous note for source.

5.2 Neutral Umpires

The ‘Gatting incident’ reopened old wounds. The Indian all-rounder, Ravi Shastri (now coach of the Indian team) recalled that, in India’s tour of Pakistan in 1982–83, the two Pakistani umpires, one of whom was Rana, provided their opponents with two additional players; in 1984, the New Zealand captain, Jeremy Coney, had threatened to take his side off the field after an appeal for lbw against Javed Miandad was turned down by Rana.[5] Given this history, the publicity associated with the Gatting incident sounded the death knell for partisan umpires. In 1994, the International Cricket Council (ICC) required every Test match to have at least one neutral umpire (that is, not from one of the playing countries) and, in 2002, this was extended to both umpires being neutral starting with India’s tour of the West Indies between April and June that year. The effects of these changes were immediately evident: as Leamon and Jones (2021) show, the gap between the proportion of lbw dismissals of home and away batsmen fell with one neutral umpire and vanished when both umpires were neutral.[6]

Because of travel restrictions during the Covid crisis, the practice of two neutral umpires for Test Matches was suspended: the umpires for the 2021 Test Series between England and India, played in India in February–March 2021, were Indian, and the umpires for the 2020–21 Test Series between Australia and India, played in Australia between December 2020 and January 2021, were Australian. However, even in the pre-Covid years the practice of having neutral Test umpires was never applied to women’s Test Matches. All the officials associated with the (four-day) women’s Australia–England Test Match, played in Taunton, 18–21 July 2019, were English while all the officials associated with the (four-day) women’s Australia–England Test Match, played in Sydney, 9–12 November 2017, were Australian. Similarly, all the officials associated with the (four-day) women’s India–South Africa Test Match, played in Mysore, 16–19 November 2014, were Indian. So, all the benefits of

[5] https://www.crictracker.com/december-8-1987-when-mike-gatting-and-shakoor-rana-spat-threatened-to-end-the-tour/ (accessed 31 July 2021).

[6] In the welter of these changes, the irony was that it was Pakistan that set the ball rolling towards neutral umpires when it appointed two Indian umpires, V. K. Ramaswamy and Piloo Reporter, to adjudicate on its Test Match with the West Indies in Lahore on 7 November 1986. This was then followed by two English umpires, John Hampshire and John Holder, being appointed for Pakistan’s home series with India in 1989–90.

neutral umpires in Test Matches were exclusive to men's Test Matches and bypassed the women's game entirely.

5.3 The Decision Review System

The next innovation, after neutral umpires, in the adjudication of play in cricket was the Decision Review System (DRS) which was introduced in 2009 for Test Matches, starting with the first Test between New Zealand and Pakistan on 24 November 2009 in Dunedin, and extended to One Day Internationals (ODIs) in 2011, starting with the first ODI between England and Australia on 16 January 2011 in Melbourne. Under DRS, either the fielders or the batters may request a review of any decision (except 'timed out') taken by the on-field umpires regarding a batter's dismissal or exoneration; in practice, reviews usually involve lbw, stumping, runout, or a fair catch.

This chapter focuses on decisions in which the umpire adjudicates on lbw appeals by the fielding side and, in particular, when a judgement is required as to whether a ball which did not pitch outside the leg stump and which made contact with the batter in line with the stumps, without first striking the bat, would have gone on to hit or miss the stumps.[7] As Steen (2011, p. 1429) describes it:

> [P]erhaps the most arduous task to confront any match official, adjudging a batsman lbw involves a daunting sequence of assessments: whether the ball struck bat before body; whether it pitched in line with the stumps; whether it would have hit, bypassed or bounced over the stumps; whether the batsman's stride had taken him too far down the pitch for safe appraisal; whether he used his pads with the express intent of obstructing the ball. A small matter, then, of depth perception, geometry, probability, and psychology.

After an appeal for lbw an umpire can decide to either accept or reject the appeal. Depending on the outcome, either the fielders or the batters can ask to have the decision reviewed by a third umpire. This person, located in a room in the stadium, has access to technology which allows them to replay the event on a TV monitor, this replay being supplemented by ball-tracking ('Hawk-Eye') and

[7] See box on the lbw rules. For a complete account of the rules and regulations surrounding the use of DRS see ICC (2017, Appendix D).

ball-contact (‘Snickometer’ and ‘Hotspot’) technologies.[8] The *minimum* number of cameras for the use of DRS and the appointment of a third umpire is six: four runout cameras and two to follow the ball. (These camera positions are shown in Figure 5.1.) After reviewing the evidence based on this technology, the third umpire advises the on-field umpire whether: (i) the batsman was ‘out’; (ii) ‘not out’; (iii) the evidence was ‘inconclusive’. In the light of this advice, the on-field umpire either holds to their original decision or reverses it.

<Figure 5.1>

An important aspect of the DRS system is that if, upon review, the third umpire cannot answer the question posed (namely, was the on-field umpire right in accepting/rejecting an lbw appeal?) with a ‘high degree of confidence’, then the review is *inconclusive* and the on-field umpire’s decision stands. This is known as ‘umpire’s call’: unless there is conclusive evidence that the on-field umpire was wrong, their decision stands. There is one specific circumstance in which the review might be inconclusive with respect to lbw decisions: when Hawk-Eye predicts that only *part* of the ball would have struck the stumps, as against either the centre of the ball striking the stumps or the ball missing the stumps altogether. In the face of this ambiguity during a review, ‘umpire’s call’ prevails: if the on-field decision was ‘out’, then, after review, the batter is declared to be ‘out’; if the on-field decision was ‘not out’ then, after review, the batter is declared to be ‘not out’.

A feature of DRS is to limit the number of permissible reviews that each team is allowed. Currently, this is two per team for a Test Match (increased to three in the COVID era) and one per team for an ODI (increased to two in the COVID era). If a team’s review of an on-field decision is unsuccessful, it “loses” a review meaning that the number of reviews available to it is reduced by one – in the pre-COVID period, a team with two unsuccessful reviews would have no more reviews left.[9]

[8] The ICC requires that ‘the Home Board will ensure a separate room is provided for the third umpire and that they have access to television monitors and direct sound link with the television control broadcast director to facilitate as many replays as necessary to assist him [sic] in making a decision’ (ICC, 2017, Appendix D, p. 77).
[9] The caveat to this are situations in which an lbw is sufficiently close for the unsuccessful team to be allowed to retain the review – that is number of available reviews is not reduced by the unsuccessful review.

Gender Issues

In terms of gender parity, however, the story of DRS bears a striking resemblance to that of neutral umpires: through its regular usage in men's games, most of the benefits of DRS have accrued to men who, through constant exposure to DRS, have become adept at its use. On the other hand, the sporadic use of DRS in women's matches means that the benefits of DRS to women are only occasional; moreover, these occasional benefits have been further diluted because the intermittent availability of DRS to women cricketers means that they have found it difficult to learn the art of using the system effectively.

DRS was made available in a women's bilateral series for the first time during the West Indies women's T20 tour of England, 21–30 September 2020. Prior to that, DRS was available during the 10 televised games of the women's 50-over World Cup in 2017 (won by England) and in all the matches of the women's T20 World Cups of 2018 and 2020 (both won by Australia). Outside the ambit of World Cups, however, women have scarcely benefited from DRS: New Zealand used DRS in their 2019 series against India and again in their 2020 series against South Africa, and DRS was available when England played India in a (four-day) Test Match in Bristol 16–19 June 2021. The Indian women's captain, Mithali Raj, has called for more consistent use of DRS to allow players to get used to the system,[10] while the English captain, Heather Knight, attributed the absence of DRS in the women's game to a lack of money: 'I'd imagine the reason, as usual in women's cricket, is money, as to why we don't have it [DRS]'.[11]

Learning how to use DRS effectively involves both training in its use and a slow accretion of experience through constant exposure to it. The problem is particularly acute for women cricketers: not only have women had limited exposure to DRS but also, as Nicholson (2020) points out, teams do not have good decision-making processes in place. For example, when the fielding side considers a review, it is important that the enthusiasm of the bowler does not unduly influence the captain's judgement; when the batters consider a review for an adverse lbw decision, it is important that the non-striker gives

[10] See: https://www.news18.com/cricketnext/news/use-of-drs-should-be-consistent-mithali-2052203.html (accessed 23 July 2021).
[11] See: https://www.espncricinfo.com/story/drs-to-make-maiden-appearance-in-a-women-s-bilateral-series-in-england-during-west-indies-tour-1232797 (accessed 23 July 2021).

the aggrieved batsman his frank view on the likelihood of the review succeeding. Even England's national women's team, who in the context of the women's game are relatively well resourced, do not get facilities to practise the use of DRS.

An illustration of the importance of learning through experience is provided by the Indian men's team. Before it was formally introduced in 2009, DRS was trialled in the India versus Sri Lanka men's Test series of 24 July to 10 August 2008, held in Sri Lanka; there were 12 decisions that were overturned by DRS in this trial but only one of these benefitted India.[12] There is a learning process to the effective use of DRS. Although Indian men continue to be laggards in terms of using DRS effectively, their success rate of 1 in 12 has improved considerably since their Sri Lankan tour of 2008 and, indeed, is today higher than that of Australia, South Africa, and Sri Lanka.

Since September 2017 (when the ICC stopped resetting reviews after the 80th over), there have been 1,141 reviews in Test Matches of which 325 (or 28%) were successful in reversing the on-field umpire's decision.[13] The success rate, however, varied with country. Pakistan's men had the highest success rate, managing to overturn 34.6% of on-field decisions, followed by England with a success rate of 32.4%. At the other end of the spectrum were: India (27%), Australia (26.6%), South Africa (25.4%), and Sri Lanka (23.3%). A particular feature of India's attitude towards DRS is that its top six (male) batsmen squandered reviews when they were at the crease with only 29.8% of batter reviews, compared to England's 48%, succeeding.[14] This is probably a consequence of the exalted status accorded in India to its cricketers, with its 'star' batters loath to surrender their place at the crease even when the on-field umpire required them to leave.

Umpire's Call

The practice of 'umpire's call' raises hackles with some players, including the legendary Indian player, Sachin Tendulkar:

---

[12] Leamon and Jones (2021).

[13] The practice of resetting reviews after 80 overs meant that teams were frivolous in asking for reviews as the 80th over approached knowing they would, after the reset, they would recover the lost reviews.

[14] These figures are from https://www.espncricinfo.com/story/which-teams-use-the-drs-best-pakistan-ace-it-new-zealand-go-conservative-1219826 (accessed 23 July 2021).

> Sachin reckons that the concept is flawed and argued that if the ball is hitting the stumps, even marginally, during the ball-tracking segment of the DRS, it should be given out. 'One thing I don't agree with, with the ICC, is the DRS they've been using for quite some time. It is the lbw decision where more than 50% of the ball must be hitting the stumps for the on-field decision to be overturned. The only reason they (the batsman or the bowler) have gone upstairs is because they are unhappy with the on-field decision, so when the decision goes to the third umpire, let the technology take over; just like in Tennis — it is either in or out, there's nothing in between', he said in a video chat with Brian Lara.[15]

Notwithstanding opposition by some past and current cricketers to 'umpire's call' — for example, Shane Warne and Virat Kohli, in addition to Tendulkar — the ICC has decided to retain the system.[16]

The error made by those opposing 'umpire's call' is believing that there is a perfect match between Hawk-Eye's virtual world and the real world: if, during an lbw review, Hawk-Eye shows the ball to be hitting/clipping/missing the stumps then it is assumed that that is exactly what would have happened. In the minds of such critics of 'umpire's call', the virtual and the real overlap perfectly. As Collins and Evans (2008) have commented: 'for a number of years after the introduction of Hawk-Eye, cricket commentators would simply remark on what Hawk-Eye showed on the screen giving the impression, perhaps inadvertently, that the virtual reality represented what would have actually happened had the pad not been struck' (p. 288).[17] Even when participants feel that Hawk-Eye's imagery contradicted the evidence of their eyes they had no option but to accept Hawk-Eye's judgement. As the cricket commentator, Harsha Bhogle, remarked after the Test Match at Trent Bridge between England and Australia (10–14 July 2013): 'I mean just about everybody on the ground said that's hitting outside leg [Phil Hughes was the batsman] and Hawk-Eye showed it was actually pitching in line, and then you start to wonder, were we wrong or is technology wrong?'.[18]

---

[15] See: https://indianexpress.com/article/explained/sachin-tendulkar-problem-with-decision-review-system-6502257/ (accessed 22 July 2021).
[16] See: https://www.skysports.com/cricket/news/12123/12263073/icc-decides-to-stick-with-drs-umpires-call-despite-concerns-being-raised-over-its-use (accessed 22 July 2021).
[17] See also Collins *et al.* (2016).
[18] 'Indian Cricket does without the Decision Review System', ABC Radio (PM with Mark Colvin) http://www.abc.net.au/news/2013-07-15/indian-cricket-does-without-decision-review-system/4821714?section=sport (accessed 22 July 2021).

This chapter considers the perhaps heretical notion that Hawk-Eye might make mistakes and analyses the consequences of such errors of technology. It shows that in the presence of errors made by technology (Hawk-Eye) and by humans (on-field umpires) the overall error rate can be decomposed into a 'technology error rate' and a 'human error rate'. The relevant point is then which of these two sources makes the larger contribution to the overall error rate? This then implies that there are two alternative ways for improving decision making in cricket: improved technology (through, say, better cameras) or improved umpires (through, say, better training). Which of these is more cost effective depends upon the associated costs of the two alternatives.

5.4 Hawk-Eye's Working and its Imperfections

The essence of Hawk-Eye is to feed images from several cameras — the ICC specifies a minimum of six strategically placed around the ground (see Figure 5.1 for their location) — into a computer. Every time the cameras click (say, with a frame rate of *x* times per second) they provide a 'data point'. The computer takes these data points and reconstructs the trajectory of the ball by analysing the pixels in the images. Because of the limited frame rate, there will be gaps between the data points which are 'filled' by using an algorithm which calculates the *most likely* trajectory between data points. The higher the frame rate, the smaller will be the distance between data points and, consequently, the more reliable will be the technology (Collins and Evans, 2008).

For example, a cricket ball bowled at 80mph travels approximately120 feet per second. A speed of 120 frames per second would mean the ball travelled a foot between successive frames with the computer interpolating the ball's trajectory (of a foot) between the two frames. This possibly underpins Hawk-Eye's claim that it needs one to two feet of travel after the ball has pitched to accurately track its post-bounce trajectory:[19] a frame speed of 120 per second would supply three data points in the two feet of travel after bouncing — enough to track its trajectory. However, it has been suggested that Hawk-Eye takes its feed from standard broadcast cameras with frame rates of around 30 frames per second.[20] If this was true, then it would imply the ball would travel four feet between two frames and would have to travel eight feet before three data points could be garnered.

[19] Paul Hawkins, Managing Director of Hawk-Eye Innovations, in Rajesh (2003).
[20] Owens, Harris and Stennett (2003).

This is the technology that Hawk-Eye applies both to line decisions in tennis and to lbw decisions in cricket: it relies on cameras to capture images of the ball and then uses a computer to reconstruct the ball's trajectory (including interpolation of the trajectory between data points) and then places this trajectory in the context of the playing conditions (a tennis court or a cricket pitch) to produce a virtual reality of play as it (might have) happened. This virtual reality used in conjunction with the game's rules then leads to a decision. However, compared to tennis, Hawk-Eye does more in cricket: it additionally extrapolates the trajectory of the ball from the point it strikes the batsman (the end point for which camera/computer-generated data exist) to generate a purely *hypothetical* trajectory (unsupported by any data) which predicts whether the ball, *if it had not struck the batsman*, would have gone on to hit the stumps and, furthermore, if it would have hit the stumps, the closeness of the contact between ball and stumps.

In order to analyse the degree of overlap between the virtual and the real worlds one needs to enquire about the margins of error associated with Hawk-Eye's *tracking* performance (up to the point of contact with the batsman, when it has data points to guide it) and its *predictive* performance (after contact with the batsman, when it does not have any data to guide it, relating to whether the ball would have gone on to hit the stumps). As Collins and Evans (2008) note, the only information that is available about the reliability of Hawk-Eye is an assertion by Paul Hawkins, the founder of Hawk-Eye, that 'in most cases, Hawk-Eye's output in accurate to within five millimetres [0.2 inches] in predicting the path of the ball', and 'even when the point of contact is very close to the pitch of the ball, the accuracy levels are still within 20 mm [0.8 inches]'.[21] There is no reference to the dispersion of the error or to the confidence intervals surrounding the mean error.[22] Nor is there any distinction made between Hawk-Eye's tracking and its predictive reliability.[23]

<Figure 5.2>

---

[21] See Rajesh (2006). Remembering that the circumference of a cricket ball is 224–229 mm, the self-confessed error (with a frame speed of 120 per second) could be up to 10% of the size of the ball.

[22] In tennis, Hawk-Eye's website reports a mean error of 3.66 mm, again without any accompanying information.

[23] However, Paul Hawkins has been quick to criticise the reliability of Hawk-Eye's rival, Virtual Eye — the system used in Australia — which he claims is up to nine times less accurate (Williamson, 2010).

If one supposes that the errors made by Hawk-Eye are generated from a normal distribution, then one knows that 68% of the errors will lie within one standard deviation (σ) of the mean (μ) and that 95% of the errors will lie within two standard deviations of the mean (see Figure 5.2) but, crucially, *one does not know what the standard deviation is*. However, using the method of 'Mean Squares' [24] one can estimate the standard deviation as: $\sigma = \sqrt{\frac{\pi}{2}} \times \mu = 1.254 \times 5 = 6.27$ where $\pi=22/7$ and $\mu=5$. From this we can infer that, in nearly one in three cases, Hawk-Eye's error would be greater than 11 mm (0.43 inches) and that in 5% of cases (1 in 20), Hawk-Eye's error would be greater than 17 mm (0.67 inches). It should be emphasised that these calculations are made taking Hawk-Eye's own estimates of its average error of 5 mm, without any reference to additional complicating factors such as the current shape, the hardness, and the texture of the ball, the state of the pitch, the atmospheric conditions etc.

<Figure 5.3>

In Figure 5.3 the red ball is shown by Hawk-Eye to be clipping the stump but in one in three cases this representation would be an error and it would have missed the stumps as the black ball does. On the other hand, more than half the green ball is shown to be hitting the stumps but, again, in one in three cases this representation would be an error and it would only clip the stumps as the red ball does. If the on-field umpire had declared the batsman 'out', DRS would have supported the decision based on the red ball but would have overturned it based on the black ball. On the other hand, if the on-field decision had been 'not out', DRS would have supported the decision based on the red ball but would have overturned it based on the green ball. But, regardless of the on-field decision, there would be (at least) a one-in-three chance that Hawk-Eye had got it wrong.

5.5 The Analytical Framework for Estimating Umpiring Errors

Suppose there were N appeals (for lbw) which, after the on-field umpire had given their decision, were referred to the third umpire. The outcomes of these are classified as in Table 5.1. Of the N appeals that were reviewed, the on-field umpire gave a total of N_A 'outs' and N_R 'not outs'. The third

[24] This method also is known as the 'Peters' Method' after Peters (1856) and is also described in Fisher (1920).

umpire judged, based on technology-assisted evidence, that of the *N* lbw appeals that were reviewed: N_X were 'out', N_Y were 'not out', and N_Z were 'inconclusive'.

<Table 5.1>

The on-field umpire's 'positive error rate' (*PER*) and 'negative error rate' (*NER*) are defined, respectively, as the fractions of their positive (accepting the appeal: event *A*) and negative (rejecting the appeal: event *R*) decisions which, on review by the third umpire, were reversed: $\frac{N_{YA}}{N_A}$ and $\frac{N_{YR}}{N_R}$; *PER* is the fraction of cases in which an umpire *wrongly* judged a batsman to be out and *NER* is the fraction of cases in which an umpire *wrongly* judged a batsman to be not out. One can, in passing, refer to an on-field umpire as being a 'bowler's umpire' if *PER*>*NER* and as a 'batsman's umpire' if *PER*<*NER*.

The on-field umpire's overall error rate (*OER*) is the fraction of the total number of reviews which were reversed:

$$OER = \frac{N_Y}{N} = \frac{N_{YA} + N_{YR}}{N} = \frac{N_{YA}}{N_A}\frac{N_A}{N} + \frac{N_{YR}}{N_R}\frac{N_R}{N} = PER \times p + NER \times (1 - p) \quad (5.1)$$

where: *p* is the proportion of appeals the on-field umpire upheld and *(1-p)* is the proportion they refused.

The assumption behind DRS, as applied to reviews of lbw decisions, is that Hawk-Eye's ball-tracking technology is perfectly reliable so that the $N_Y = N_{YA} + N_{YR}$ decisions that were reversed all represented on-field umpiring errors, all of which, after review, were corrected. Consequently, DRS led to an improvement in the accuracy of umpiring decisions and that, indeed, is the main argument put forward for justifying the cost of the expensive technology needed to implement the system.[25]

[25] Hawk-Eye officials admitted that their technology made an error in a decision to give Pakistan opener Shan Masood out lbw in the second Test against New Zealand in Dubai, 17–21 November 2014. These officials claimed that Masood's bat and the square-leg umpire obscured a crucial couple of frames in the ball's flight, leading to an input error by Hawk-Eye's operator. See: https://www.espncricinfo.com/story/hawk-eye-admits-technical-error-in-masood-dismissal-809021 (accessed 2 August 2021).

Analysis of 'Out' Decisions for lbw

As the previous section argued, Hawk-Eye's infallibility, both in terms of tracking and prediction, cannot be taken for granted: although one does not have details about its proneness to error, one does know that it is capable of mistakes.[26] In this sub-section we analyse the implications of imperfect technology for DRS when the on-field umpire gives an 'out' decision.

Suppose that Hawk-Eye's ball-tracking technology records a '+' value if it predicts that the ball was going on to hit the stumps and a '-' value if it predicts that the ball would have missed the stumps. The *reliability* of Hawk-Eye (which is known) is given by the pair of values α and β, where α is the probability of a *positive* Hawk-Eye value *if the ball was going to hit the stumps* and β is the probability of a *negative* Hawk-Eye value *if the ball was going to miss the stumps*, $\alpha > \beta, 0 \leq \alpha,\beta \leq 1$. The reliability of Hawk-Eye is detailed below:

The Reliability of Hawk-Eye for 'out' lbw decisions

P(+|H) = α	P(+|M) = 1-β
P(-|H) = 1-α	P(-|M) = β

In statistical parlance, $P(+|H) = \alpha$ is referred to as the *sensitivity* of the test and $P(-|M) = \beta$ is referred to as the *specificity* of the test. The sensitivity of a test is the proportion of 'hits' (H) that are correctly classified (+): $P(+|H)$; the specificity of a test is the proportion of 'misses' (M) that are correctly classified (-): $P(-|M)$. Since Hawk-Eye is a ball-tracking technology, it is assumed that it is as successful in classifying hits as it is in classifying misses or, in other words, its sensitivity is equal to its specificity. The implication of this is that $\alpha=\beta$.

Suppose further that the *prior* probabilities of the batsman being given 'out' justifiably (that is, event H occurring) and erroneously (that is, event M occurring) are, respectively, θ and $1-\theta$ where $0 \leq \theta \leq 1$. In other words, before Hawk-Eye's evidence under DRS is scrutinised, these are the *prior* beliefs that the on-field umpire was right/wrong in giving the batsman out. *The point of examining the evidence is to alter one's prior belief in its light.*

[26] In 2007, there were three infamous examples in tennis of Hawk-Eye 'errors' when the decision of a linesman in calling a ball as 'out' was reversed on appeal after Hawk-Eye declared the ball as 'in' (see Collins and Evans, 2008 for details).

Analysis of On-field 'Out' Decisions for lbw

The mathematical analysis of lbw decisions made by the on-field umpire which declared a batsman to be out is set out in Box 5.2, below with the main text setting out a numerical example. Suppose that 1,000 cases in which the on-field umpire judged that a batsman was 'out' lbw are referred under DRS to the third umpire, with the only question being whether the ball (either wholly or in part) was going on to hit the stumps (event *H*) or miss them altogether (event *M*).[27] Suppose that the prior hypothesis was that on-field umpires got 85% of such lbw decisions right: in other words, $P(H)=\theta = 0.85$ and $P(M)=(1-\theta)=0.15$. Suppose also that trials had shown Hawk-Eye to be 95% accurate, meaning that 95% of balls that hit the stumps, and 95% of those that missed the stumps (as defined above), would have been correctly predicted by Hawk-Eye. In other words, $P(+\mid H)=P(-\mid M)=\alpha=0.95$.

Then, Hawk-Eye would report a total of 185 'negative values'. First, of the 1,000 referrals for an out decision, the on-field umpire would have got it *right* 85% of the time so that in 850 reviews the ball would have hit the stumps. However, because Hawk-Eye is fallible — with a reliability rate of 95% — it would judge 5% of these 850 balls, which the on-field umpire *rightly* thought were going to hit the stumps, as missing the stumps (P-|H) = 0.05). Second, of the 1,000 referrals for an on-field 'out' decision, the on-field umpire would have got it *wrong* 15% of the time so that, in 150 reviews, the ball, which the on-field umpire thought was going to hit the stumps, would have missed the stumps. Hawk-Eye, with a 95% reliability rate, would judge that in 95% of these 150 reviews, for which the on-field umpire *wrongly* believed that the ball was going to hit the stumps, would have missed the stumps (P(-|M) = 0.95). So, in total, Hawk-Eye would regard 185 on-field decisions of 'out' as on-field errors: 5% of 850 + 95% of 150 *and accordingly reverse them all*.

The on-field umpire would be deemed to have an error rate of 18.5% implying that the prior hypothesis of a 15% on-field error rate needed to be revised upwards in the light of evidence from Hawk-Eye. However, of the 185 reversals, only 143 = 0.95 × 150 (or 77% of total reversals) were the result of umpire error. These are the 150 lbw appeals which the on-field umpire got wrong by giving a

[27] In other words, the ball was a legitimate delivery which pitched in line and struck in line without any suggestion of an 'inside edge'.

batter ‘out’ to balls that would have missed the stumps, 95% of which would have been reversed by Hawk-Eye (that is, those cases in which Hawk-Eye reported negative values for balls missing the stumps); the remaining 42 reversals (23%) were the result of Hawk-Eye’s error, when it mistakenly thought that a ball would have missed the stumps when, in fact, it was going on to hit them and these reversals should not have been made. Consequently, the true on-field umpiring error rate was only 14.3% and the prior hypothesis of a 15% on-field umpire error rate was, if anything, a slight exaggeration.

In the light of the above analysis one can decompose the total of 185 reversals in two parts: (i) that part due to Hawk-Eye error, and (ii) that part due to on-field umpire error:

$$\left[(1-0.95)\times 0.85+0.95\times(1-0.85)\right]\times 1000=\left[\underbrace{(0.05)\times 0.85}_{\text{Hawk-Eye error rate}}+\underbrace{0.95\times 0.15}_{\text{Umpire error rate}}\right]\times 1000$$

If Hawk-Eye never got it wrong, so that that *α = P(+|H) = P(-|M) = 1*, all the errors would emanate from the on-field umpire, with an error rate of 15%, and 150 of the 1,000 reviews of on-field ‘out’ decisions for lbw would be reversed. However, with a fallible Hawk-Eye, the number of reversals increases as *α* takes values less than 1. In the above example, a 95% reliability rate for Hawk-Eye would have led to185 reversals: all of these would have been put down to on-field umpiring errors but, in fact, only 143 of these reversals could have been so attributed; the remaining 42 reversals were due to Hawk-Eye’s imperfections.

Box 5.2: General Analysis of On-Field 'Out' lbw Decisions

Of the total of N_A referrals for which the on-field umpire had given 'out' (see Table 5.1), the prior belief is that in $\theta \times N_A$ cases the ball would have hit the stumps and that in $(1-\theta) \times N_A$ cases it would have missed them altogether. The operation of DRS is such that all on-field 'out' decisions for which Hawk-Eye reported a *negative* value (that is, suggested that the ball would miss the stumps) would be reversed. The reliability of the test, noted in the table above, is such that Hawk-Eye would report $(1-\alpha) \times \theta \times N_A$ negative (-) values for the $\theta \times N_A$ cases in which the ball would have hit the stumps and $\beta \times (1-\theta) \times N_A$ negative (-) values for the $(1-\theta) \times N_A$ cases in which the ball would have missed the stumps.

So, the total number of cases for which Hawk-Eye would report a negative value is (remembering, by assumption that $\alpha=\beta$): $(1-\alpha) \times \theta \times N_A + \alpha \times (1-\theta) \times N_A$. All these decisions would be reversed under DRS. So, according to DRS, the on-field umpire's *error rate* (that is, the proportion of on-field decisions that were reversed on review) is:

$$\frac{[(1-\alpha)\times\theta+\alpha\times(1-\theta)]\times N_A}{N_A} = (1-\alpha)\times\theta+\alpha\times(1-\theta) \qquad (5.2)$$

However, this almost certainly overstates the on-field umpire's error rate because DRS should reverse only those decisions for which Hawk-Eye's value is negative *and* the ball would have missed the stumps, that is, the event: -|M. The number of such events is $\alpha \times (1-\theta) \times N_A$ and it is only these that should be reversed. Consequently, the *overall* error rate, reported in equation (5.2) for the on-field out decisions for lbw, can be decomposed into a *Hawk-Eye error rate* and an (on-field) *umpire error rate* as follows:

$$(1-\alpha)\times\theta+\alpha\times(1-\theta) = \underbrace{(1-\alpha)\times\theta}_{\text{Hawk-Eye error rate}} + \underbrace{\alpha\times(1-\theta)}_{\text{Umpire error rate}} \qquad (5.3)$$

If Hawk-Eye never got it wrong, $\alpha=1$ and all the errors emanate from the on-field umpire with an error rate of $1-\theta$. However, if Hawk-Eye is less than perfect, so that $\alpha<1$, then some of the DRS reversals (based on a negative Hawk-Eye value) will be wrongly made and will be the result of Hawk-Eye's fallibility. If Hawk-Eye and the on-field umpire are equally prone to error ($\alpha=\theta$), then from equation (5.3), *half* the reversals made by DRS should not have occurred because they were the result of Hawk-Eye reporting a negative value for balls that were going on to hit the stumps. This proportion of 'incorrect DRS reversals' falls as α rises reaching zero when $\alpha=1$.

Analysis of On-field 'Not Out' Decisions for lbw

The mathematical analysis of lbw decisions made by the on-field umpire which declared a batsman to be not out is set out in Box 5.3, below with the main text setting out a numerical example. Suppose that 1,000 cases in which the on-field umpire judged that a batsman was 'not out' lbw are referred, under DRS, to the third umpire, with the only question being whether the ball was going on to hit the stumps. [28] Now the issue that is in in doubt is whether the *centre* of the ball was going to 'hit' the stumps (event *H* is that the ball would have hit the stumps as defined) or whether the ball was going to 'miss' the stumps meaning it was *either* going to miss the stumps altogether *or* only a part of it was going to make contact with the stumps (event *M* is that the ball would have missed the stumps as defined).

Suppose that the prior hypothesis was that on-field umpires got 90% of such lbw decisions right: in other words, $P(H)=\theta = 0.9$ and $P(M) = (1-\theta) = 0.1$. Suppose also that trials had shown Hawk-Eye to be 95% accurate, meaning that 95% of balls that hit the stumps, and 95% of those that missed the stumps (as defined above), would have been correctly predicted by Hawk-Eye. In other words, $P(+|H) = P(-|M) = \alpha = 0.95$.

Then, Hawk-Eye would report a total of 140 'positive values'. First, of the 1,000 referrals for a 'not out' decision, the on-field umpire would have got it *right* 90% of the time so that in 900 reviews the ball would have missed the stumps. However, because Hawk-Eye is fallible — with a reliability rate of 95% — it would judge 5% of these 900 balls, which the on-field umpire *rightly* thought were missing the stumps, as going on to hit the stumps $(P+|M) = 0.05)$. Second, of the 1,000 referrals for an on-field 'not out' decision, the on-field umpire would have got it *wrong* 10% of the time so that, in 100 reviews, the ball, which the on-field umpire thought was going to miss the stumps, would have hit the stumps. Hawk-Eye, with a 95% reliability rate, would judge that in 95% of these 100 reviews, for which the on-field umpire *wrongly* believed that the ball was going to miss the stumps, the ball would have hit the stumps (P(+|H) = 0.95). So, in total, Hawk-Eye would regard 140

[28] In other words, the ball was a legitimate delivery which pitched in line and struck in line without any suggestion of an 'inside edge'.

on-field lbw decisions of 'not out' as on-field errors: 5% of 900 + 95% of 100 *and accordingly reverse them all*.

The on-field umpire would be deemed to have an error rate of 14% implying that the prior hypothesis of a 10% error rate needed to be revised upwards in the light of evidence from Hawk-Eye. However, of the 140 reversals, only 95 (68%) were due to umpire error. These were the 100 cases which the on-field umpire got wrong by giving a batter 'not out' to balls that would have hit the stumps, 95% of which would have been reversed by Hawk-Eye (that is, those cases in which Hawk-Eye reported positive values for balls hitting the stumps). The remaining 45 reversals (32%) were the result of Hawk-Eye's error when it mistakenly thought that a ball would have hit the stumps when, in fact, it was missing the stumps. Consequently, the true on-field umpiring error rate was only 9.5% and the prior hypothesis of a 10% on-field umpire error rate was, if anything, a slight overestimate.[29]

As with on-field out decisions for lbw, discussed earlier, one can decompose the total of 140 reversals in two parts: (i) that part due to Hawk-Eye error, and (ii) that part due to on-field umpire error:

$$\left[(1-0.95)\times 0.9+0.95\times(1-0.9)\right]\times 1000=\left[\underbrace{(0.05)\times 0.9}_{\text{Hawk-Eye error rate}}+\underbrace{0.95\times 0.1}_{\text{Umpire error rate}}\right]\times 1000$$

If Hawk-Eye never got it wrong, so that that *α = P(+|H) = P(-|M) = 1*, all the errors would emanate from the on-field umpire, with an error rate of 10%, and 100 of the 1,000 reviews of on-field 'not out' decisions for lbw would be reversed. However, with a fallible Hawk-Eye, the number of reversals increases as *α* takes values less than 1. In the above example, a 95% reliability rate for Hawk-Eye would have led to 140 reversals: all of these would have been put down to on-field umpiring errors but, in fact, only 95 of these reversals could have been so attributed; the remaining 45 reversals were due to Hawk-Eye's imperfections.

In general, as set out in detail in Box 5.4, Provided that Hawk-Eye's reliability is greater than 50%, the proportion of the total number of reviews that are reversed will fall as the competence of the on-field umpire increases. Similarly, for a given degree of on-field umpire's competence, provided it

[29] The above analysis can be set in the Bayesian framework discussed in chapter 2 (see Borooah, 2016).

exceeds 50%, the proportion of the total number of reviews that are reversed will rise as Hawk-Eye's reliability improves.

Box 5.3: General Analysis of On-field 'Not Out' lbw Decisions

Of the total of N_R reviews for which the on-field umpire had given 'not out' (see Table 5.1), the prior belief is that in $\theta \times N_R$ cases the ball would have missed the stumps and that in $(1-\theta) \times N_R$ cases it would have hit them. The operation of DRS is such that all on-field 'not out' decisions for which Hawk-Eye reported a *positive* value (that is, suggested that the ball would have hit the stumps) would be reversed. The reliability of the test, noted above, is such that Hawk-Eye would report $(1-\beta) \times \theta \times N_R$ positive (+) values for the $\theta \times N_R$ cases in which the ball would have missed the stumps and $\alpha \times (1-\theta) \times N_R$ negative (+) values for the $(1-\theta) \times N_R$ cases in which the ball would have 'hit' the stumps. So, the total number of cases for which Hawk-Eye would report a positive value are (remembering, by assumption that *sensitivity* = *specificity*, or $\alpha=\beta$): $[(1-\beta) \times \theta + \beta \times (1-\theta)] \times N_R$. All these decisions would be reversed under DRS. So, according to DRS, the on-field umpire's *error rate* (that is, the proportion of his 'not out' decisions that were reversed on review) is:

$$\frac{[(1-\beta)\times\theta+\beta\times(1-\theta)]\times N_R}{N_R} = (1-\beta)\times\theta+\beta\times(1-\theta) \qquad (5.4)$$

However, this almost certainly overstates the on-field umpire's error rate because DRS should reverse only those decisions for which Hawk-Eye's value is positive *and* the ball would have hit the stumps. These are $\beta \times (1-\theta) \times N_R$. Consequently, the *overall* error rate, reported in equation (5.4) for the on-field 'not out' decisions for lbw, can be decomposed into a *Hawk-Eye error rate* and an (on-field) *umpire error rate* as follows:

$$(1-\beta)\times\theta+\beta\times(1-\theta) = \underbrace{(1-\beta)\times\theta}_{\text{Hawk-Eye error rate}} + \underbrace{\beta\times(1-\theta)}_{\text{Umpire error rate}} \qquad (5.5)$$

Of course, if Hawk-Eye is infallible ($\beta^*=1$), then all the errors emanate from the on-field umpire. However, if Hawk-Eye is less than perfect, then some of the DRS reversals (based on a positive Hawk-Eye value) will be wrongly made and engendered by Hawk-Eye's fallibility. If Hawk-Eye and the on-field umpire are equally prone to error ($\beta^*=\theta^*$), then from equation (5.5), *half* the reversals made by DRS should not have been made because they were the result of Hawk-Eye reporting a positive value for balls that were going on to miss the stumps. This proportion of 'incorrect DRS reversals' falls as β rises, reaching zero when $\beta=1$.

Box 5.4: The Dynamics of On-Field Decision Reversals

Provided that Hawk-Eye's reliability is greater than 50% (that is $\alpha > 1/2$), the proportion of the total number of reviews that are reversed, $(1-\alpha)\times\theta+\alpha\times(1-\theta)$, will fall as the competence of the on-field umpire increases because:

$$\partial[(1-\alpha)\theta+\alpha(1-\theta)]/\partial\theta = 1-2\alpha < 0, \text{ for } \alpha > 1/2 .$$

Similarly, for a given degree of on-field umpire's competence, $\theta > 1/2$, the proportion of the total number of reviews that are reversed, $(1-\alpha)\times\theta+\alpha\times(1-\theta)$, will rise as Hawk-Eye's reliability improves because:

$$\partial[(1-\alpha)\theta+\alpha(1-\theta)]/\partial\alpha = 1-2\theta < 0, \text{ for } \theta > 1/2 .$$

5.6 The Cost of Technology

The above analysis showed that there were two competing ways of reducing umpiring errors:

1. Improving the accuracy of Hawk-Eye's ball-tracking technology.
2. Improving on-field decision making.

This, in turn, raises the question: which of the two methods is more cost effective? Is it cheaper to reduce umpiring inaccuracy by improving on-field standards or by improving technology? This, however, raises some prior questions: what is the purpose of using technology? And how much does technology cost and what are the implications for cricket?

The most cited aim of technology-assisted umpiring via DRS is to 'eliminate the howler'. Yet, this purpose is not so easily achieved. A team may have squandered its limited number of appeals — two in Test Cricket, one in ODIs — only to find, when faced with an egregiously bad decision, that it has no further reviews left with which to 'eliminate the howler'. In the third Ashes Test Match, played at Headingley on 22–26 August 2019, Australia would have won had they reviewed a 'not out' decision for lbw against Ben Stokes. Replays showed that, under DRS, the on-field decision would have had to be reversed but, because Australia had exhausted their reviews, Stokes survived and England went on to win the match and, with it, the Ashes.

Moreover, even if DRS could eliminate howlers, their number in cricket, notwithstanding the sound and fury they generate among journalists and commentators, are few and far between. For example, the loud demands for DRS to be used in Australia's Big Bash League were based on two bad decisions, both against Usman Khwaja: the first, in a match between Perth Scorchers and Sydney Thunder, reprieved him when the umpire failed to detect an obvious nick which carried to the wicket-keeper; in the second incident, in a match between Sydney Thunder and Melbourne Stars, he was given out, caught behind, despite not nicking the ball.[30] Between 2001 and 2020, there were just six shockingly bad on-field decisions in Test Matches.[31]

[30] See: https://www.abc.net.au/news/2020-12-23/cricket-calls-grow-for-drs-in-bbl/13009504 (accessed 27 July 2021).
[31] See: https://www.odds.com.au/news/watch-6-of-crickets-worst-umpiring-howlers/ (accessed 27 July 2021).

The economics of DRS depend, therefore, on its cost. In 2011, it was estimated that the full-blown, international version of DRS (that is, with Hawk-Eye, Hotspot, and Ultra-Edge) would cost around US$60,000 per match day.[32] Suppose that one assumes that technological improvements in the intervening decade have meant that, by 2021, the real cost of DRS fell so that the cash outlay needed for DRS remained at US$60,000.[33] Then the cost of eliminating these howlers — even if DRS could achieve this, which, for the reasons given above, is doubtful — would have been US$18 million or US$300,000 per howler.[34] Those who clamour for the universal application of DRS, based on occasionally poor on-field decisions, should reflect on the costs of using DRS to correct these.

Indeed, the high cost of the full-blown version of DRS has led to the search for 'cut-price' versions, without all the bells and whistles, which, though unsuitable for international games, could be used in domestic matches. Cricket Australia, recognising that the cost of a full-blown DRS constrains regional venues from hosting matches, has proposed a watered-down version suitable for Big Bash League (BBL) and Women's Big Bash League (WBBL) matches (Cameron, 2020). The Board of Cricket Control in India (BCCI) uses a version of DRS for its Ranji Trophy matches which doesn't have Hawk-Eye, Hotspot, or Ultra-Edge, but uses just the pitch map and the stumps microphone (Pandey, 2020), while Bangladesh has used a version of DRS without Hotspot or Ultra-Edge for its Bangladesh Premier League (BPL) matches.[35] In both the Ranji Trophy and the BPL matches, however, the use of a cut-price DRS has led to on-field embarrassment (Pandey, 2020 and footnote 33).

It is relevant to ask what one gets for the expenditure associated with DRS. In the first Ashes Test Match of 2013 — Trent Bridge, 10–14 July — there were five on-field decisions which were reversed by DRS, of which one reversal was a clear mistake.[36] According to the ICC the four

---

[32] See: https://www.espncricinfo.com/story/decision-review-system-drs-technology-expensive-unreliable-niranjan-shah-520736 (accessed 18 August 2021).

[33] This is a generous assumption because it has been reported that a full package would have cost US$100,000 in 2019. https://www.thecricketer.com/Topics/globalgame/bangladesh_premier_league_caught_out_using_cut-price_version_of_drs_.html (accessed 18 August 2021).

[34] Six five-day Tests is 30 days of DRS at US$60,000 per day.

[35] See: https://www.thecricketer.com/Topics/globalgame/bangladesh_premier_league_caught_out_using_cut-price_version_of_drs_.html (accessed 18 August 2021).

[36] In England's second innings, the Australians asked for a review of a not out lbw decision in favour of Jonathan Trott. This reversed the not out decision but only because Hotspot was not available to the third umpire

remaining reversals raised the percentage of correct decisions from 90.3% to 95.8%: a 5.5 percentage point improvement for a US$300,000 outlay or US$54,545 *per point* improvement. The ICC's calculations were as follows: the two on-field umpires (Dar and Dharmasena) and the third umpire (Erasmus) made 72 decisions between them and, of these, seven were 'errors', implying a correct umpiring decision rate of 90.3%. Of these seven errors, four were corrected after review meaning that, post-review, there were only three errors from 72 decisions implying a 95.8% correct decision rate.[37]

But this is surely the wrong question, compounded by the fact it is based upon an erroneous assumption. The right question is to ask what the percentage of correct umpiring decisions would have been *if DRS had not been used*. If one excludes the lbw against Trott from the list of on-field umpire errors — since it was a technology error — there were only six errors (out of 72) from the *on-field* umpires, implying a correct on-field umpiring decision rate of 91.7%. This provides a true comparison because it is the 'correct decision rate', in the absence of DRS.

The erroneous assumption is the belief in Hawk-Eye's infallibility — namely, that all four post-review reversals 'righted' a 'wrong'. In fact, with Hughes' dismissal in Australia's second innings, everyone (including the on-field umpire) believed the ball had pitched outside the line. Why should one trust Hawk-Eye's interpolated tracking — which judged the ball to have pitched in line — more than the collective evidence of hundreds of pairs of eyes which said not? If one regards this reversal as a Hawk-Eye error, then the on-field umpires made only *five* errors (Hughes was correctly judged by the on-field umpire to be not out) for a correct *on-field* umpiring decision rate of 93.1%, *absent DRS*. In the presence of DRS, three of the reversals were correctly made — so the number of errors was reduced to two — but, since one reversal (Hughes) was incorrectly made, the number of post-DRS errors was increased by one (Hawk-Eye error) for a total of three post-DRS errors, implying a 95.8% correct (post-DRS) decision rate. So, the use of DRS raised the correct decision rate

for that decision; had it been available, it would have shown a clear inside edge vindicating the original not out decision.

[37] 'Ashes: ICC publicly defends umpires, decision review system', https://www.thehindu.com/sport/cricket/After-contentious-Ashes-opener-ICC-defends-DRS/article12007938.ece (accessed 29 August 2021).

from 93.1% to 95.8%, a gain of 2.7 points for an outlay of US$300,000 — or at a price of over US$100,000 per point improvement.

So, those who glibly quote the ICC's estimates about the improvement in umpiring standards that the use of DRS has brought about — as measured by the rise in the 'correct' decision rate — should: (i) bear in mind that the ICC's estimates of this improvement are based on the belief that Hawk-Eye is infallible; and (ii) consider the price at which this improvement is being bought. For the 10–14 July 2013 Ashes Test Match, this price, even based on the sanguine view of the ICC, was nearly US$55,000 per point improvement; on the basis of the more reasoned view, articulated above, it was over US$100,000 per point improvement. If 'getting it right' is so important to international cricket then, arguably, the same gains could be harvested, at much lower cost, by investing in more training of umpires and a more determined search to increase the size of the pool of good umpires.

In fact, DRS is not used by players to eliminate the howler but is employed rather, by both batters and fielders, to gamble on overturning on-field decisions which they think might have been marginal. Batters, when they are given out lbw, review the decision gambling on Hawk-Eye's ball-tracking showing the black, rather than the green, ball of Figure 5.3. Fielders, when an lbw decision goes against them, review the decision gambling on Hawk-Eye's ball-tracking showing the green, rather than the black, ball of Figure 5.3. In both cases, there is a reasonable likelihood of the gamble succeeding.

There is, however, a more insidious effect of DRS, which is not often commented upon, and that is 'umpire capture' by DRS. It is usually assumed that in cricket, umpires and the DRS's Hawk-Eye operate independently of each other. But if there is synergy between the two, then the on-field umpires' views on the likely outcome of an lbw appeal could be influenced by their experience of what Hawk-Eye is likely to predict as the outcome. This is what is meant by 'umpire capture' — some part of an umpire's decision is based upon an anticipation of what Hawk-Eye's prediction might be.

Leamon and Jones (2021) suggest as much when they write that the 'biggest impact of the DRS was not about changing the umpire's mind after he had made his decision. It was about changing the initial decision itself'. Specifically, Leamon and Jones draw attention to the fact that, with spinners bowling, umpires were more likely to give batters, playing on the front foot, out lbw than previously because, in their experience, Hawk-Eye showed such deliveries as going on to hit the stumps. Leamon and Jones (ibid.) reckon that, with the batter on the front foot, spinners had a 15% chance of a successful lbw appeal in the pre-DRS (pre- 24 November 2009) days which, by 2018, rose to 20%. Also, over time, umpires have learnt about the intricacies of DRS outcomes: according to Leamon and Jones (ibid), the proportion of successful lbw appeals climbed from one-in-five in 2014 to nearly one-in-three by 2020.

From the perspective of umpires this alignment of their judgement with Hawk-Eye — even if subconscious — makes perfect sense. If the error rate of umpires is based on the proportion of their on-field decisions that are reversed by DRS, and if public opinion of their ability as umpires is directly proportional to this error rate, then it is rational to reduce this error rate by asking, if only in the most subliminal terms, 'what would Hawk-Eye have shown?' — and then to adjust their decisions accordingly. This notion of 'umpire capture' — which is not dissimilar to the concept of 'regulatory capture' in economics, whereby regulated industries can influence the regulator — raises the question of on-field independence when umpires might have half an eye on what Hawk-Eye might think of their decision.[38]

5.7 Conclusions

Historians looking back on cricketing developments in the 21st century might well be justified in viewing DRS as an albatross around cricket's neck, impeding its progress towards a wider geographical and social spread of the game. First, DRS has failed in its ostensible aim of 'eliminating the howler'. This is because players, instead of waiting for the shockingly bad decision to appear and then asking to have it reviewed, make speculative referrals of on-field decisions they think might have been marginal, gambling that Hawk-Eye will uphold their review. Consequently, when the bad on-field decision does come along, as inevitably it must, they often find they have no reviews left with which to challenge it. So, the weeping and gnashing of teeth after every glaring umpiring error, followed by a chorus of voices demanding the installation of DRS to prevent these, serves no purpose: DRS cannot, and will not, 'eliminate the howler'.

[38] See Stigler (1971) for his seminal paper on regulatory capture.

Second, DRS seems to have created among several influential cricketers the illusion that the virtual world created by Hawk-Eye is the real world: if Hawk-Eye shows the ball to have been clipping the stumps then that is what surely would have happened. The fact that Hawk-Eye makes a prediction about the likely path of the ball and that, like all predictions, this is accompanied by a margin of error is lost in the discussion. Here a false analogy is drawn between a batter being out, bowled by a ball which trimmed the bails, and being given not out lbw to an identical ball. The former event occurred in the real world, the latter in Hawk-Eye's virtual world; the first is a statement of what really happened, the second, a speculation about what might have happened. The use of 'umpire's call' is a step towards recognising that the real and virtual worlds are different, and it is to preserve this important distinction that 'umpires call' should and must be retained.

If 'umpires call' were to be abandoned, then cricket would become like tennis, a game in which the virtual and the real are conflated: the tennis ball shown by Hawk-Eye to be just clipping the baseline must have done so, without any ifs and buts, regardless that the line judge called it 'out'; similarly, the ball missing the line by a hair's breadth must, without prevarication, have done so regardless that the line judge called it 'in'. To view the world of computer simulations as identical with that of the world that we inhabit requires a suspension of disbelief and it is this suspension, embodied in the absence of 'line judge's call', that causes tennis to use Hawk-Eye badly. Conversely, it is the unwillingness to conflate the two worlds, encapsulated in the use of 'umpire's call', that leads cricket to make more intelligent use of the same technology (Collins and Evans, 2012).

Third, the use of Hawk-Eye presents the very real danger of 'umpire capture' meaning that umpires, before arriving at their on-field decision, might start to ask themselves: 'what would Hawk-Eye show?'. This then poses the issue of interdependence between technological and human judgement with the tail of technology wagging the on-field dog. So, when umpires start to give more lbws against batters on the front foot to spinners, were the batters in fact out? Or was it because, if the on-field decision were to be reviewed, Hawk-Eye would have shown them to be out? The convention in cricket is that if the umpire cannot be certain that the ball would have hit the stumps, or if certainty is artificially injected by technology, then the on-field decision must be 'not out'.

Lastly, the most pernicious aspect of DRS is its cost, estimated at US$60,000 per match day. This cost, which must be borne by local cricket associations, creates an apartheid system between the 'haves' who can afford DRS and the 'have nots' who cannot. Many of the teams that participate in cricket's one-day and T20 World Cups do not use DRS in their own countries and their only experience with it is every two years during World Cups.

Even within countries that use DRS, its use is restricted to major cricket grounds usually located in metropolitan centres. Teams that are not scheduled to play at such venues must do without DRS. This particularly affects women cricketers. For example, of the 20 Test Matches that Indian women played in India, several were played at outlying venues: in Mumbai, they played at the Mumbai Gymkhana, not at the Brabourne or the Wankhede stadiums; in Delhi, they played at the Jamia Millia Cricket Ground; in Kolkata, their match was at the Cricket and Football Ground, not at Eden Gardens. Several of their matches were at locations that had never hosted a men's Test Match: Jammu (Molana Azad Stadium), Jamshedpur (Keenan Stadium), Lucknow (K.D. Singh Stadium), Mysore (Ganghotri Glades), Patna (Moin-ul-Haq Stadium), and Vapi (Bilakhiya Stadium).

Relegating women's matches to far-flung venues generates a vicious cycle: because the prior belief of cricket administrators is that such matches will be poorly attended they are assigned to locations and venues that are not well known and, in many instances, difficult to get to; out-of-the-way venues then lead to small attendances which, to complete the circle, only serves to confirm the prior belief of a lack of public interest in seeing women play cricket. To break this circle, women's international matches need to be played at major venues with DRS employed. But, since DRS costs money, cricket administrators are loath to use it for matches which they think will not attract large audiences and, consequently, farm these games out to grounds where there is no prospect of employing the technological innovations that male cricketers take for granted.

The mandatory use of DRS in men's international matches, and in the games associated with certain franchises like the Indian Premier League (IPL), inhibits the geographical spread of the game. If one of the aims of cricket is to secure a wider coverage of the game by taking it to audiences in locations unused to staging major matches, then this aim is thwarted by the costs associated with DRS: smaller locations and venues might like to host big matches but are prevented from doing so because this would require an investment in the paraphernalia of DRS which they cannot afford. Consequently, the straitjacket of DRS restricts such matches to the major cricketing centres. This may not matter too much in smaller countries like England, where most people live within easy reach of major grounds, but it is an important issue in larger cricketing nations like Australia, India, and South Africa.

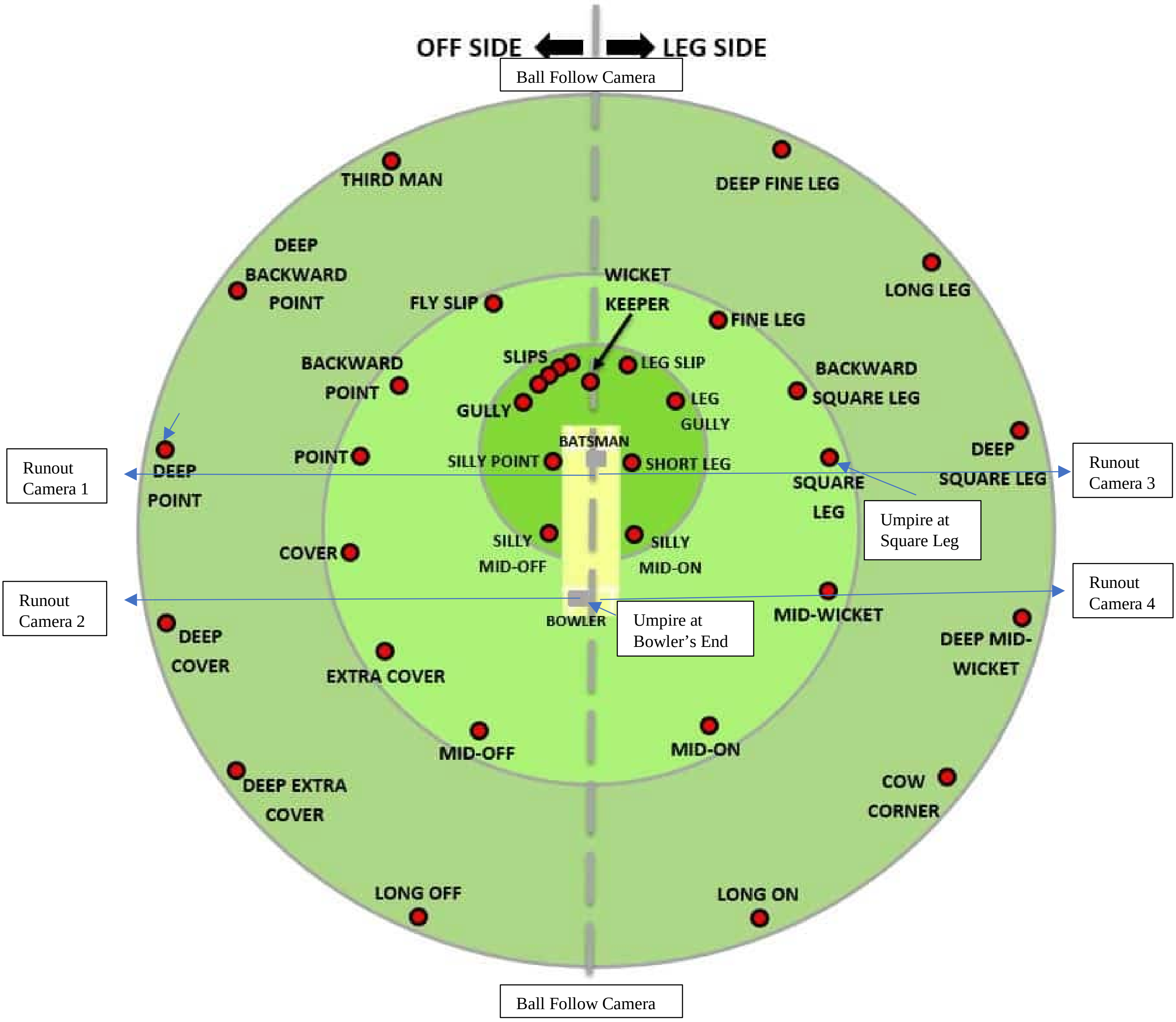
But a broader question is this. When international cricket has so many pressing problems, foremost among which must be corruption and illegal betting, an over-crowded international calendar which risks players' well-being by keeping them constantly playing matches, and tension between national cricket boards and cricket franchises like the IPL teams, why are the ICC and cricket commentators — particularly in England — so obsessed with DRS and so keen promote it?

One clue is provided by Collins and Evans (2012) and Collins *et. al.* (2016) when they write that technology has completely transformed spectators' experience, at home or at the match. Big screens at the match provide replays, often in slow motion, of crucial passages of play; at home, expert commentary aided by different camera angles provides the viewer with a perspective on play which he/she could not have imagined even a decade ago. The presence of all this technology means that spectators have little tolerance for what Collins and Evans (2012) term the 'transparent injustice' of poor decisions by on-field umpires. Perhaps, in almost equal measure, spectators have an appreciation of 'transparent justice', when technology confirms seemingly difficult decisions made by on-field umpires as having been correct. Moreover, punctuating play with episodes of technology-based appraisals of on-field umpires' decisions injects an element of suspense to the spectating experience and so enhances it. Lastly, given that talking about a game is an important aspect of sport, technology gives spectators further debating and discussion points as they conduct post-mortems of the game based on information provided by slow-motion replays, camera angles, stump microphones etc.

So, although this chapter has been critical of DRS, all these factors lead to the conclusion that DRS is here to stay - it has no choice but to advance and improve. As Collins (2010) concluded, umpiring is about justice, not about accuracy. The dividing line is between close calls and obvious errors. Technology should be used to avoid errors that are plain to all but, in situations where no obvious error exists, human judgement should be sovereign.

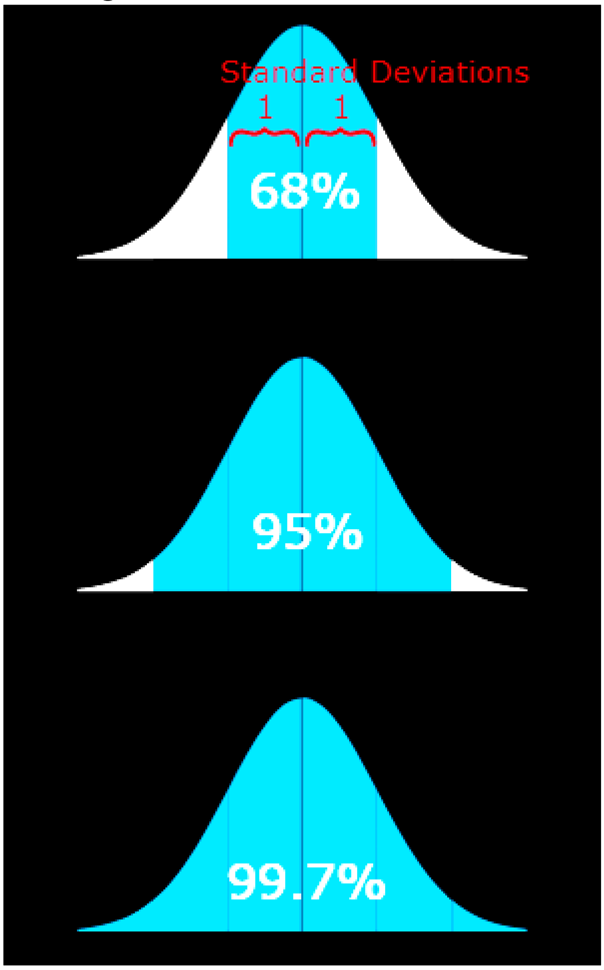
One way of achieving this is to restrict the number of available referrals to just one per Test innings instead of the two (three in the Covid-era) that are currently allowed. This will focus the minds of players on reviewing only those decisions about which they are genuinely aggrieved. An additional reform might be to not allow sides to retain reviews that go against them, regardless of whether 'umpire's call' applies. This will discourage speculative reviews: after all, if one gambles on a horse winning, one's money is lost whether it loses by a head or by several yards. Having said all this, the use of technology-driven sporting enhancements is too deeply embedded in cricket — in large part because they have done much to increase spectators' enjoyment — for cricket to turn its back on DRS, the child that this technology has spawned.

Figure 5.1: Fielding Positions in Cricket



Source: cricketershub.com and ICC (2017, Appendix D)

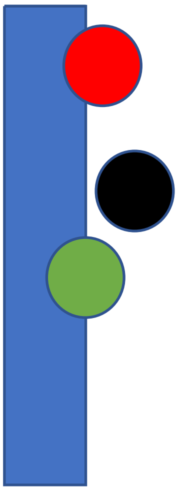
Figure 5.2: The Normal Distribution



68% of observations are within one standard deviation (sd) of the mean
95% of observations are within two sd of the mean
99.7% of observations are within three sd of mean

Source: https://www.mathsisfun.com/data/standard-normal-distribution.html

Figure 5.3: Hawk-Eye Error



Source: Own Diagram

Table 5.1: Classification of DRS outcomes

		On-field Umpire		
		Out	Not out	Totals
Third Umpire	Agrees	N_{XA}	N_{XR}	N_X
	Disagrees	N_{YA}	N_{YR}	N_Y
	Cannot say	N_{ZA}	N_{ZR}	N_Z
		N_A	N_R	N

Source: Own Table

References

Borooah, V.K. (2016), "Upstairs and Downstairs: The Imperfections of Cricket's Decision Review System", *Journal of Sports Economics*, **17**: 64–85.

Cameron, L. (2020), *CA Flags 'Big-Bash Specific' DRS for 2021–22 Summer*, Melbourne: Cricket Australia. https://www.cricket.com.au/news/decision-review-system-drs-introduction-big-bash-league-bbl11-alistair-dobson/2020-12-28 (accessed 18 August 2021).

Collins, H. (2010), "The Philosophy of Umpiring and the Introduction of Decision-Aid Technology", *Journal of the Philosophy of Sport*, **37**: 135–146.

Collins, H., and Evans, R. (2008), "You Cannot Be Serious! Public Understanding of Technology with Special Reference to 'Hawk-Eye'", *Public Understanding of Science*, **17**: 283–308.

Collins, H., and Evans, R. (2012), "Sport-Decision Aids and the 'CSI-effect': Why Cricket Uses Hawk-Eye Well and Tennis Uses it Badly", *Public Understanding of Science*, **21**: 904–921.

Collins, H., Evans, R., and Higgins, C. (2016), *Bad Call: Technology's Attack on Umpires and How to Fix it*, Cambridge (MA): The MIT Press.

Fisher, R.A. (1920), "A Mathematical Examination of the Methods of Determining the Accuracy of an Observation by the Mean Square and the Mean Square Error", *Monthly Notices of the Royal Astronomical Society*, **80**: 758–770.

ICC (International Cricket Council) (2017), *Men's Test Match Playing Conditions.* ICC-Men's-Test-Match-Playing-Conditions-2017-Code-FINAL-051017.pdf (accessed 22 July 2021).

Leamon, N., and Jones, B. (2021), *Hitting Against the Spin*, London: Constable, Little Brown Book Group.

Nicholson, R. (2020), "How Can Women's Cricket Learn to Use the DRS Better?", ESPN Cricinfo 4 March. https://www.espncricinfo.com/story/raf-nicholson-how-can-women-s-cricket-learn-to-use-the-drs-better-1218360 (accessed 23 July 2021).

Owens, N., Harris, C., and Stennett, C. (2003) "Hawk-Eye Tennis System," in *VIE 2003: International Conference on Visual Information Engineering: Ideas, Applications, Experience*, 7–9 July, University of Surrey, Guildford (182–185).

Pandey, D. (2020), “Limited DRS Has Teams Fretting: BCCI Says Full Version Too Expensive”, *The Indian Express* 12 March. https://indianexpress.com/article/sports/cricket/limited-drs-has-teams-fretting-bcci-says-full-version-too-expensive-6309734/ (accessed 18 August 2021).

Peters, C.A.F. (1856), “Uber die Bestimmung des wahrscheimlichen Fehlers einer Beobachtung aus den Abweichungen der Beobachtungen von ihrem arithmetischen Mittel,” *Astronomische Nachrichen*, **44**: 30–31.

Rajesh, S. (2003), “Give Hawk-Eye a Chance”, ESPN Cricinfo, 13 June. http://www.espncricinfo.com/ci/content/story/125938.html (accessed 24 July 2021).

Rajesh, S. (2006), “A Threat or an Advantage”, ESPN Cricinfo, 18 December. http://www.espncricinfo.com/ci/content/story/250359.html (accessed 24 July 2021).

Steen, R. (2011), “Going Upstairs: The Decision Review System – a Velvet Revolution or the Thin Edge of an Ethical Wedge?”, *Sport in Society*, **14**: 1428–1440.

Stigler, G.J. (1971), “The Theory of Economic Regulation”, *The Bell Journal of Economics and Management Science*, **2**: 3–21.

Williamson, L. (2010), “Techno Boffins Don’t See Hawk-Eye-to-Virtual Eye as Reliability of Video Evidence Questioned”, *Mail Online*, 10 December. http://www.dailymail.co.uk/sport/cricket/article-1337280/ASHES-2010-Techno-boffins-dont-Hawk-eye-Virtual-Eye-reliability-video-evidence-questioned.html (accessed 24 July 2021).