Author/s:
Pinder, S;Easton, S;Stern, S

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Key words: Risk-Taking Behaviour, Interim Performance, Real Options

JEL Codes: G13, G31

Stephen Easton [a], Sean Pinder [b], Steven Stern [c]

[a] *Newcastle Business School, University of Newcastle, NSW 2308, Australia. Email: steve.easton@newcastle.edu.au*

[b] *Corresponding Author: Department of Finance, University of Melbourne, VIC 3010, Australia. Email: spinder@unimelb.edu.au. Phone: 61 3 8344 5101. Fax: 61 3 8344 1900*

[c] *Bond Business School, Bond University, QLD 4226, Australia. Email: sstern@bond.edu.au*

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DR. SEAN PINDER (Orcid ID : 0000-0003-3083-6047)

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Abstract

Changes in risk-taking behaviour based on interim performance are examined in high-stakes competition. A real options framework is used to provide a richer characterisation of risk-taking behaviour than examined in extant studies. This framework is applied to an examination of ball-by-ball data from 1207 cricket matches. Consistent with modelled expectations, risk taking is found to increase (decrease) at a decreasing rate following below par (above par) interim performance. This result is especially strong in situations where the resources remaining are low, a result predicted by the real options model.

1. Introduction

A real options framework is used in this paper to provide a more complete theoretical and empirical examination of the functional form of the relation between interim performance and risk taking than that provided in extant studies. These studies all hypothesise simple and incomplete representations of the relation between interim performance and risk taking, with, for example, Genakos and Pagliero (2012, p. 783) suggesting that the relation between interim performance and risk taking is an empirical issue. The relations tested are either binomial (for example, that risk taking is low (high) following good (bad) previous-stage performance), or linear (for example, that risk taking is lower (higher) following higher (lower) previous-stage performance).

This paper therefore extends the economics literature that has examined dynamic risk-taking behaviour in the contexts of, for example, sporting contests and financial markets. For example, Grund and Gurtler (2005) studied soccer matches and found that losing teams were more likely to make risky substitutions. Grund, Hocker and Zimmermann (2013) also found that trailing basketball teams were more likely to increase their use of risky three-point shots. Ozbeklik and Smith (2014) analysed risk-taking behaviour in match-play professional golf tournaments that are characterized by head-to-head contests. They report that players who are trailing in a contest increase their risk taking, where risk taking is measured as either the number of holes conceded by the trailing player or the cross-sectional standard deviation of a player's score relative to the par score on each sample hole.

Within the financial economics literature, Brown, Harlow, and Starks (1996), Chevalier and Ellison (1997), Kempf, Ruenzi and Thiele (2009) and Taylor (2003) show that mutual funds with relatively low mid-year performance increase fund volatility. For those fund managers that have performed poorly, the incentive is to increase their relative risk level given that they benefit by trying to improve their ranking by year end. That is, managers finding themselves positioned at an interim assessment period as losers (that is, having performed worse than average) need to generate a return over the remainder of the assessment period that is sufficient to make up their first period deficit. One way in which they achieve this result is by altering fund risk during the rest of the period to a level that is larger than that expected for the interim winners (that is, managers who performed better than average).

On the other hand, those managers that have high interim returns compared to their peers want to maintain those high returns and are less inclined to take risky positions and may even scale back their risk positions in an attempt to lock in their present return level.[1]

[1] The endogeneity of risk-taking behaviour is of course embedded within the corporate finance literature with its long history of studying potential agency problems between debt and equity holders. Specifically, the asset substitution effect discussed by Jensen and Meckling (1976) and Myers (1977) suggests that when the market value of a firm's assets are low relative to the claims by debtholders on those assets, managers seeking to increase the value of equity might replace low-risk projects with high-risk counterparts, even where the higher risk projects have a negative net present value.

The current paper makes an important contribution to the extant literature by employing a real options framework to establish a set of testable predictions as to not only the direction of the relationship between interim performance and risk-taking by participants in a contest, but also how that relationship evolves in a non-linear fashion as well as how it changes with the stage of the contest at hand.

As detailed below, the rules of limited overs cricket provide the opportunity to examine the functional form of this risk-taking relation. In this paper we first derive that functional relation, and then use ball-by-ball data from 1207 matches to provide an empirical examination.

2. Functional Form of Relation between Interim Performance and Risk Taking

In a two-team sporting contest, the probability of a team winning may be modelled as the value of a binary call option C. The terminal payoff to this binary call option may be expressed as:

$$Payoff_T = \begin{cases} 1 \; if \; S_T - P_T \geq 0 \\ 0 \; if \; S_T - P_T < 0 \end{cases} \qquad (1)$$

Where S_T is the score of the team at the completion of the game at time T, and P_T is one plus the score of the other team at the completion of the game.[2]

It follows that at any time t prior to the completion of the game, the value of the option may be expressed as a function of four parameters: namely the score of the team at time t S_t; the expected, or employing golfing parlance the "par" score P_t, for the team at time t; the time remaining in the game $\tau = T - t$; and the volatility (σ) of the underlying diffusion process of

[2] The real options framework used in this study dates back to the foundation analysis by Marschak (1949), and Arrow (1968), and was developed by, for example, Bernanke (1983), Brennan and Schwartz (1985), Pindyck (1991) and Dixit and Pindyck (1993). Bachelier (1900) modelled option prices using arithmetic Brownian motion. For a discussion, see Sullivan and Weithers (1991). In the context of a sporting contest, an arithmetic Brownian process has the necessary feature of permitting negative values of the underlying asset where the asset value in the present case is the current score of the chasing team (S) minus the par score for that team (P).

the score differential $S_t - P_t$.[3] If we assume that the diffusion process of the score differential follows an arithmetic Brownian process with an expected mean of zero and a standard deviation of σ, then the probability of a team winning the contest is the value of a binary option and may be expressed as:

$$C = N(d) \text{ where } = \frac{(S_t - P_t)}{\sigma\sqrt{\tau}}, \qquad (2)$$

N (d) is the cumulative distribution function of the standard normal distribution, and S_t, P_t, σ and τ are as previously defined.

The relationship between the score differential at a particular stage of the game and the probability of winning is described in Figure 1 for three representative levels of volatility (high, medium and low).

[Insert Figure 1 here]

As shown in Figure 1, when the score differential for a team ($S_t - P_t$) is negative, an increase in volatility increases the probability of winning. Conversely, when the score differential is positive, a decrease in volatility increases the probability of winning. It may be noted that under the assumption of a symmetrical diffusion process, when the score differential is zero, volatility has no impact on the expected outcome of the contest.

To gain further insight into the relationship between the incentive to increase risk taking and the value of the option embedded in a sporting contest, we may also consider the option's vega, that is, the sensitivity of the option's value to changes in volatility. Vega may be expressed as:

$$\nu = N'(d).\frac{(P-S)}{\sigma^2\sqrt{\tau}} \text{ where } N'(d) = \frac{1}{\sqrt{2\pi}}.e^{-\frac{d^2}{2}} \text{ and } d = \frac{(S-P)}{\sigma\sqrt{\tau}} \qquad (3)$$

[3] Unlike an option written on an asset such as a stock, the estimation of the probability of winning a sporting contest in a binary option setting does not require the specification of an interest rate as there is no opportunity cost associated with the delayed receipt of the terminal payoff.

The relationship between the sensitivity of this option's value to changes in volatility (vega (ν)) and the money-ness of the option as represented by the score differential ($S_t - P_t$) is provided in Figure 2.

[Insert Figure 2 here]

Figure 2 illustrates two points concerning the relationship between changes in risk and the value of the binary option. Firstly, vega is always positive when the option is out of the money which provides that where a team is behind the par score in a sporting contest they have an incentive to increase risk. Conversely, vega is always negative when the option is in the money which dictates that where a team is ahead of the par score there is an incentive to decrease risk taking.

Second, the incentive to increase risk is non-linear in the money-ness of the option. For both deep out-of-the-money and deep-in-the-money options the incentive to further increase or decrease risk is minimal as it has little effect on the value of the option. The key objective of the paper is to test whether risk-taking behaviour by contest participants is consistent with this non-linear relationship between risk and the value of the embedded option.

In order to utilise a real-options framework, it is necessary to have a dynamic setting where it is possible to determine the interim performance or money-ness of the situation faced by competitors, as well as the remaining life of the option. The game of limited overs cricket and rules that are formally integrated into it provide that setting. Cricket is one of the major sports in the UK, Australia, New Zealand, South Africa and the Caribbean islands and the most popular sport in India, Pakistan, Sri Lanka and Bangladesh. There are 106 member countries of the peak professional body - the International Cricket Council (ICC).[4]

The essence of the game of cricket (in its limited overs format) is that each team has a turn in offense and defence. The objective of the first team is to score as many "runs" as possible over the 300 occasions that the defensive team delivers the ball to the batting team. The batting team has the opportunity for 11 batsmen to bat – but they must bat in pairs; therefore

[4] For a comprehensive coverage of the rules of cricket, see Booth (2015). It may be noted that cricket has previously been used to examine reference-dependent preferences - see Gauriot and Page (2015).

after 10 batsmen lose their wickets (are declared "out" by the umpires) the offensive part of the game for that team is concluded. The task for the team batting second is simply to exceed the score achieved by the team batting first.

In this analysis we are interested in the behaviour of the team batting second. At any stage of this part of the game, the current score of the team batting second S_t is known. But importantly, the expected or par score P_t, for this team at time t is also known, as is a rule-based measure that captures τ, the remaining life of the option. To understand these features of the game of cricket, it is necessary to briefly outline the Duckworth-Lewis-Stern (DLS) system (see Duckworth and Lewis (1998) and (2004) and Stern (2009)) that is formally integrated into the rules of limited overs cricket.

The DLS system is a statistically-based model of the expected proportion of a team's runs yet to be scored as a function of the number of balls remaining to be delivered by the defensive team and the number of wickets that remain. In particular, these estimated proportions represent the amount of run-scoring resources (R_t) that remain to a batting team at any point. The model is fitted based on observed run-scoring patterns from modern international limited-overs matches and is regularly updated so as to keep pace with changes in the way in which games are played.

Therefore, in examining risk-taking behaviour in cricket matches, the calculation of R_t enables the removal of the assumption made above that the resources available to teams are constant during the game. Resources remaining, R_t, is a single parameter constructed to be identical to the value of τ in the option framework detailed above. Therefore in all subsequent discussion τ will be replaced by R_t.

The DLS system also provides on a ball-by-ball basis the par score P_t for the team batting second. This value is simply the final score of the team batting first, multiplied by the resources that have been used so far, that is, by $1-R_t$. [5]

[5] While the DLS system is designed to achieve fairness in matches interrupted by weather or other circumstances, for our purpose the system may be used where there is no chance of the match being interrupted. Both par score and resources remaining are measures against which to assess the likelihood of the team batting second achieving the score of the team batting first. Further, while the team batting second may not know on a ball-by-ball basis the precise

With S_t, P_t and R_t known before each ball is delivered, the option pricing framework provides the setting to examine optimal risk taking behaviour. Risk taking (or volatility of the scoring process within an option framework) by the batting team in a cricket game is endogenous. It may be reduced by not seeking to score runs off every ball and defending balls that are likely to result in the loss of a wicket. But it cannot be eliminated completely. The batting team still needs to continue to score runs, and face risk, so as to ensure that its final score is equal to or exceeds the target score at the completion of the match. Similarly, risk taking may be increased by seeking to score many runs off every ball and not defending any balls. But again risk cannot be increased beyond that determined by the inherent nature and rules of the game.[6]

To detail how risk taking may be measured, consider the impact of high risk taking on changes in both the team's score and its par score. High risk taking, if successful, will result in a high number of runs being scored from a ball, that is, $S_t - S_{t-1}$ will be high. Further, the increase in resources used will be small because the only additional resource used up will be one delivered ball. Therefore $P_t - P_{t-1}$ will be small and $(S_t - S_{t-1}) - (P_t - P_{t-1})$ will be large and positive. However, if high risk taking is unsuccessful, then runs scored will be low (or zero) and therefore $(S_t - S_{t-1})$ will be zero or small. Worse, with unsuccessful risk taking a wicket will be lost, resulting in a large positive value of $P_t - P_{t-1.}$ Therefore for unsuccessful risk taking $(S_t - S_{t-1}) - (P_t - P_{t-1})$ will be large and negative. Conversely, low risk taking will be expected to result in low or zero runs being scored, and a wicket not being lost. Therefore, $(S_t - S_{t-1})$, $(P_t - P_{t-1})$, and $(S_t - S_{t-1}) - (P_t - P_{t-1})$ will be small.

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values of the par score and resources remaining, they may be expected to have estimates of those values. This situation is analogous to that of a company not knowing the future volatility of oil prices but nevertheless taking account of estimates of that volatility implied by options markets in decisions with respect to drilling activity - as documented by Kellogg (2014).

[6] The focus of this paper is on risk-taking by the team batting second (that is, the "chasing" team). Of course, the competing team (the "defending team") may also take action in the field to maximise the value of their own embedded option. However, virtually no usable data are collected about the decisions of the fielding team (for example, field placement and bowling technique. Therefore, these factors are omitted. To the extent that the actions of the defending team may obscure measurement of the risk-taking actions of the chasing team, the reported results may be expected to understate the full effect of the chasing team's risk-taking actions.

Therefore in the empirical analysis below we measure risk-taking behaviour for samples of balls as the standard deviation of the change in the team's current score relative to the par score.[7] Consistent with the real option framework, it is expected that the standard deviation of the change in the team's current score relative to the par score will increase (decrease) at a decreasing rate as the team's interim score decreases below (increases above) par.

It is also possible to examine how expected risk-taking behaviour varies with the level of resources available to the cricket team consistent with the maximisation of the value of the option embedded within the game. The sensitivity of an option's vega to resources remaining is captured by an option's veta. A key characteristic of a binary option's veta is that a change in volatility is expected to have a minor impact on options with a high level of resources remaining (a long term to expiry) as compared with options with a low level of resources remaining (a shorter term to expiry).[8] This relationship will also be examined in the empirical analysis.

3. Data Collection

The dataset contains ball-by-ball information for 1207 One Day International (ODI) matches from May 2005 to December 2014.[9] For each ball the ball number n; the number of runs scored and whether the batsman lost his wicket were recorded. These data were obtained from the ball-by-ball text commentaries available from www.cricinfo.com. These data enable

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[7] The interquartile range was also used as a measure of risk taking with the results substantively unchanged.

[8] The option's veta is calculated as the derivative of the option's vega (which itself is the derivative of the option's value with respect to volatility) with respect to resources remaining and in the case of this binary option is expressed as:

$$\frac{\delta C}{\delta R \delta \sigma} = -\frac{(P-S)(\sigma^2 R - 2P^2 + 4SP - 2S^2)e^{-\frac{(S-P)^2}{\sigma^2 R}}}{4\pi\sigma^4\sqrt{R^5}}$$

[9] Cricinfo.com is used for many studies requiring data from cricket matches; see for example, Allsopp and Clarke (2004). Detailed checking of the data was undertaken. Errors were detected in the ball-by-ball commentary for five of the matches. For two of these matches it was possible to correct these errors using the final scorecard. The remaining three matches were excluded from the analysis.

the ball-by-ball calculation of S_n, P_n, and R_n.[10] Only balls for the team batting second are relevant. In total there were 303,554 balls delivered to the team batting second. However, analysis was restricted to the balls occurring after the first 120 balls because this is the part of the game where the rules provide for the DLS system to be applied to determine the outcome. This restriction reduced the sample to 156,494 balls.

4. Analysis

The analysis of the 1207 matches is reported in Table 1 which provides an examination of the outcome of ball n based on groupings formed by ranking on the standardised score differential. The standardised score differential is defined as the lagged difference between the batting team's score and the par score after standardising by the team's resources remaining prior to ball n [that is, $(S_{n-1}-P_{n-1}) / R_{n-1}$]. Ranking on the basis of standardised score differential was used to allocate balls into 35 bins. For each bin, the range of the standardised score differential was 11, with the range of Bin 0 centred on a standardised score differential of zero. For example, Bin -1 contains all observations where, before the ball was delivered, the value of $(S_{n-1}-P_{n-1})/R_{n-1}$ was between -5.5 and -16.5 and Bin +6 contains all observations where the lagged value of $(S_{n-1}-P_{n-1})/R_{n-1}$ was between 60.5 and 71.5.[11] The statistical analysis was restricted to 35 bins to ensure that there were at least 1000 observations in each bin For comparison purposes, two additional bins consisting of all observations less (greater) than a -192.5 (+192.5) standardised score differential (Bin <-17 and Bin >17) are also included in Table 1. But these bins are excluded from subsequent regression analyses.

[Insert Table 1 here]

Recalling that Table 1 has been created by grouping observations according to the standardised score differential, $(S_{n-1}-P_{n-1}) / R_{n-1}$, as expected the mean and median values of that variable are extremely close to the midpoints of each bin. Also as expected, we see a near monotonic increase in the mean and median values of the unstandardised value of the second batting team's score relative to the par score $(S_{n-1}-P_{n-1})$ as we proceed from Bin -17 to +17.

[10] Consistent with standard option terminology the theoretical discussion referred to points in time t. Consistent with the game of cricket, in the empirical analysis points in the game are defined as balls n.

[11] Bin sizes ranging from an 8 standardised score differential to a 14 standardised score differential were also tested and the results reported in the paper, with the exception of one particular result reported below, were not significantly affected.

Again as expected, the lagged value of resources remaining, R_{n-1}, tends to be lower for bins further away from the central bin.

The second to last column of Table 1 provides the standard deviation of changes in the score differential which we use as the measure of risk taking. Risk taking decreases from the top half of groups, where teams are behind the standardised par score; to the bottom half of groups where teams are ahead of the par score. For both the top and bottom half of the groups, this behaviour is consistent with the batsmen acting in a manner that increases the value of the binary option embedded within the game, thereby increasing the likelihood of securing victory. We formally explore this relationship below, but there is also evidence that for those groups of observations that are closest within each of these halves to the central group, that we see a propensity for risk taking to behave in a near-linear fashion with group position, but this relationship weakens as we move further and further away from the central group. That is, batsmen do not continue to increase risk taking when the embedded option is deep out-of-the-money (that is, when (S−P) is large and negative on a standardised basis). Nor do they continue to decrease risk when the embedded option is deep-in-the-money. As shown in Figure 3, this non-linear relationship between risk taking and the position of the chasing team relative to the par score is apparent when we plot the standard deviation of the change in (S-P) for different levels of money-ness. This result is consistent with batsmen recognising the relative insensitivity of the value of the option embedded within the contest to changes in volatility when the option is sufficiently deep-out-of or deep-in-the-money. That is, they behave in a manner consistent with the vega of the option approaching zero when the team's score is either far behind or far ahead of the par score.

[Insert Figure 3 here]

The last column of Table 1 reports the average change in the score differential expressed on a per ball basis. This measure reflects the cost (benefit) associated with increased (decreased) risk taking. Specifically, we see that for groups at the top half of the table, where teams are behind the par score and exhibit greater risk-taking behaviour, the average result of ball n is a decline in the value of (S-P) which is consistent with the loss of wickets. Note such behaviour is compatible with optimal risk taking. While the expected outcome from high risk taking is negative, increased risk taking increases the variance of outcomes and therefore increases the probability that the team will improve its score differential such that it will win the game. In contrast, in the bottom half of Table 1, where risk taking is lower, we see an improvement in the batting team's position relative to the par score for 16 of the 17 groups of observations.

Figure 4 illustrates the relationship between the change in the score differential, $(S_n - P_n) - (S_{n-1} - P_{n-1})$, and the lagged standardised score differential, $(S_{n-1} - P_{n-1}) / R_{n-1}$. It shows the cost of increases in risk taking in terms of the expected outcome to the contest.

[Insert Figure 4 here]

To formally test the relationship between risk taking and the money-ness of the option embedded within the contest, we estimate two functional forms of this relationship using observations from the 35 groups shown in Table 1.[12]

Firstly, we estimate a linear relationship which will inform us as to whether cricketers increase risk-taking behaviour when they are behind their par score, and the option is out-of-the-money, and reduce risk taking when they are ahead of their par score and the embedded option is in-the-money. This linear functional form may be simply expressed as:

$$StdevCh_i = \alpha_0 + \alpha_1 SLagStDiff_i + \varepsilon_i \qquad (4)$$

where $StdevCh_i$ is equal to the standard deviation of the change in the team's score relative to the par score for ball n for bin i, and $LagStDiff_i$ is the average lagged standardised difference between the team's score and the par score $((S_{n-1} - P_{n-1})/R_{n-1})$ for bin i.

If cricketers behave in a manner consistent with the declining sensitivity of an option's value to changes in volatility then this suggests a non-linear relationship between $StdevCh_i$ and $LagStDiff_i$ and Equation 4 will be misspecified. Specifically, we expect to see a reverse-S-shaped relationship between risk taking and the standardised difference between the team's score and the par score at a particular stage of the game. To allow for this non-linearity, we also estimate the following logistic function from the sigmoidal family:

$$StdevCh_i = \beta_0 + \frac{\beta_1}{\left[1 + e^{-\beta_2 (LagStDiff_i - \beta_3)}\right]} + \varepsilon_i \qquad (5)$$

The results from the estimation of the linear and non-linear specifications described above are provided in Table 2.

[Insert Table 2 here]

As is evident from Panel A of Table 2, there is a strong negative relationship between the level of risk taking by cricketers and the standardised score differential. This is consistent with cricketers behaving in a manner that increases the value of the binary option embedded within the contest. Panel B provides the results for the non-linear logistic function. Similarly to the linear model, the statistically significant value of β_2 indicates that there exists a

[12] The two extreme groups capturing observations with a standardised score differential greater (less) than 192.5 (-192.5) are excluded.

negative relationship between risk taking and the standardised score differential. However, we have further evidence of the presence of two asymptotes. The left-hand asymptote is calculated as the sum of β_0 and β_1 and sits at a standard deviation of the change in score differential of approximately 4 runs. The right-hand asymptote is the estimated value of β_0 which is equal, in this case, to approximately 1.8 runs. The third estimate that the non-linear specification provides is the inflection point of the function. This point represents the standardised run differential at which participants switch from decreasing risk at an increasing rate to decreasing risk at a decreasing rate. Figures 1 and 2 suggest that the inflection point is expected to be at zero. That is, the incentive to increase risk increases at a decreasing rate as we move from a score differential of zero to a negative score differential. As the score differential becomes positive, that is the team is performing ahead of the par score, the incentive to decrease risk reduces at a decreasing rate. The estimated inflection point β_3 in this specification is when the team is approximately 36 standardised runs below the par score.[13] While the explanatory power is high for both the linear and non-linear specifications, as indicated by the adjusted R^2 values, we see that the non-linear specification dominates the linear specification as indicated by the Akaike Information Criterion statistics. To summarise, the evidence in this table is consistent with cricketers behaving in a manner that; (1) recognises the link between risk taking and the likelihood of winning a sporting contest as reflected by the impact on the value of the embedded binary option, and (2) adapts that risk-taking behaviour in a manner consistent with an understanding of the non-linear impact of risk taking on the value of the embedded option.

As noted in Section 2, a key characteristic of an option's veta is that a change in volatility is expected to have a minor impact on options with a high level of resources remaining (a long term to expiry) as compared with options with a low level of resources remaining (a shorter term to expiry). Therefore, we would expect the risk-taking behaviour documented in Panel B of Table 2 to be stronger for a subsample of observations where the resources remaining are smaller than for the subsample of observations where the resources remaining is higher. To consider this result we identify the top and bottom quartile of observations ranked by resources remaining. For each of these subsamples, we then re-estimate the non-linear relationship specified in Equation (5). The results are presented Table 3.

[Insert Table 3 here]

[13] The inflection point result is sensitive to the specification of the bin size. For example, when a bin size of 12 standardised runs is employed, instead of 11 runs, the hypothesis that the inflection point is not statistically different from zero cannot be rejected.

Firstly we consider the subsample of observations consisting of the lowest quartile of resources remaining. What is immediately clear is that the link between risk taking and the lagged standardised score differential is very similar to that reported in the whole of sample results. Specifically, we report (1) a negative relationship between risk taking and the money-ness of the embedded option, as well as the presence of (2) a left asymptote indicating that the increase in risk taking plateaus at a standard deviation of the change in score differential of just over 4 runs, and (3) a right asymptote that shows that the decrease in risk taking observed as a team gets in front of the par score tapers out at approximately 1.8 runs. In contrast, when we consider the subsample of observations where the highest level of resources are still remaining in the game, we find that there is no evidence of any relationship between risk taking and the money-ness of the embedded option. Specifically, the fact that there is no evidence of either statistically significant asymptotes or a negative relationship between risk taking and the difference between runs scored to date and the par score suggests that participants do not adjust their risk-taking strategies when the resources remaining are high. This is consistent with participants being aware of the relative insensitivity of the value of the embedded option, representing the probability of success, to changes in risk when the resources remaining to the team are relatively high.

The final issue that we consider is the consequence of different levels of risk taking to the outcome from the next ball faced by the batsmen. We test formally for evidence of the non-linearity of the relationship between the observed changes in the score differential across different levels of the standardised score differential by estimating the following logistic function:

$$ChScdiff_i = \beta_0 + \frac{\beta_1}{\left[1+e^{-\beta_2(LagStDiff_i-\beta_3)}\right]} + \varepsilon_i \qquad (6)$$

Where $ChScdiff_i$ is equal to the average change in the team's score relative to the par score for bin i and $LagStDiff_i$ is as previously defined. The results of that regression equation are presented in Table 4.

[Insert Table 4 here]

Consistent with the results reported in Table 1, we find that there is strong statistical evidence, indicated by the value of β_2, of a positive relationship between the average change in a team's score differential with the lagged value of the standardised score differential. In light of our earlier results demonstrating the negative relationship between risk taking and the lagged standardised score differential, this result is consistent with there being a significant cost (benefit) associated with increasing (decreasing) risk taking that is reflected in the expected outcome from that action. Another notable result, in terms of the non-linear dynamics of the risk-return trade-off, is that the inflection point for this estimated function is not significantly different to zero.[14] This result, together with the statistically significant values of β_0 and β_1, indicates that the benefits (and costs) of increases (decreases) in risk taking switch from increasing at an increasing rate to a decreasing rate as the standardised score differential changes from negative to positive.

5. Summary

Economic theory provides that risk-taking behaviour depends on relative performance in previous stages of a competition. Extant studies hypothesise and test simple and incomplete representations of the functional form of the relation between interim performance and risk taking. This paper uses a real options framework and ball-by-ball data from 1207 cricket matches to establish and then test key hypotheses with respect to the non-linear functional form of this relation. Consistent with expectations from standard option price modelling, risk taking increases at a decreasing rate for trailing teams, and decreases at a decreasing rate for leading teams. Furthermore, as predicted by the real options framework, we find evidence that this behaviour varies inversely with the resources remaining to the chasing team.

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[14] We also benchmark the non-linear model against a linear model and find that the reported non-linear model dominates in terms of the comparable values for AIC statistics.

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Table 1: Analysis of risk-taking behaviour across alternative aspects of intrinsic value for one-day international matches

This table reports statistics relating to the 1207 one-day international cricket matches played between May 2005 and December 2014. The variable S_n, is the batting team's score prior to ball n, P_n is the Duckworth-Lewis-Stern (DLS) par score prior to ball n, and R_n is the DLS-estimated level of resources remaining to the batting team prior to ball n.

Bin	N	Standardised runs midpoint of Bin	Average lagged $(S_{n-1}-P_{n-1})/R_{n-1}$	Median lagged $(S_{n-1}-P_{n-1})/R_{n-1}$	Average lagged $(S_{n-1}-P_{n-1})$	Median lagged $(S_{-1}-P_{t-1})$	Average lagged R	Median lagged R	Standard deviation of change in (S-P)	Average change in (S-P)
<-17	33754	NA	-1075.17	-507.49	-87.87	-82	0.163	0.150	4.008	-0.109
-17	1316	-187	-186.77	-186.56	-54.75	-57	0.293	0.303	3.841	-0.065
-16	1300	-176	-176.13	-176.19	-52.00	-54	0.295	0.309	4.168	-0.259

-15	1403	-165	-164.56	-164.33	-51.15	-52	0.311	0.315	3.825	-0.147
-14	1901	-154	-154.03	-154.12	-50.31	-51	0.327	0.329	3.717	-0.178
-13	1861	-143	-143.15	-143.28	-48.40	-51	0.338	0.358	3.907	-0.223
-12	1985	-132	-131.86	-131.74	-43.55	-45	0.330	0.339	3.679	-0.158
-11	1958	-121	-121.03	-121.06	-39.77	-41	0.329	0.340	3.432	-0.077
-10	2252	-110	-109.73	-109.66	-37.69	-41	0.344	0.368	3.448	-0.113
-9	2516	-99	-99.09	-99.14	-35.84	-39	0.362	0.391	3.636	-0.165
-8	2843	-88	-87.71	-87.56	-32.18	-34	0.367	0.391	3.347	-0.126
-7	2906	-77	-77.16	-77.23	-28.93	-30	0.375	0.392	3.423	-0.132
-6	3078	-66	-65.83	-65.86	-25.18	-26	0.382	0.399	3.110	-0.027
-5	3594	-55	-54.76	-54.60	-21.47	-22	0.392	0.403	3.029	-0.060
-4	3671	-44	-43.85	-43.73	-18.15	-19	0.415	0.438	3.184	-0.112
-3	4179	-33	-32.88	-32.86	-14.18	-15	0.431	0.470	2.977	-0.085
-2	4461	-22	-21.87	-21.85	-9.50	-10	0.434	0.463	2.853	-0.073
-1	4291	-11	-10.77	-10.65	-4.76	-5	0.444	0.474	2.630	-0.016
0	5347	0	0.11	0.00	0.04	0	0.460	0.493	2.586	-0.035
1	5527	11	11.08	11.13	5.12	5	0.461	0.488	2.380	0.031
2	6264	22	22.07	22.18	10.55	11	0.478	0.503	2.141	0.054
3	6720	33	32.87	32.78	15.77	17	0.480	0.510	2.174	0.032
4	6645	44	43.91	43.88	21.20	22	0.483	0.505	2.224	0.015
5	6131	55	54.84	54.63	25.90	27	0.473	0.489	2.030	0.031
6	6125	66	65.88	65.85	31.29	33	0.475	0.495	2.019	0.058
7	5372	77	76.85	76.72	35.90	37	0.467	0.486	1.950	0.058
8	4571	88	87.84	87.79	41.51	43	0.473	0.496	2.000	0.095
9	3977	99	99.13	99.27	45.50	48	0.459	0.483	1.955	0.178
10	3650	110	109.94	109.94	48.37	49	0.440	0.451	1.884	0.101
11	3314	121	120.72	120.53	48.88	50	0.405	0.412	1.986	0.055
12	2592	132	131.89	131.83	52.49	53	0.398	0.400	2.005	0.073
13	2170	143	142.82	142.66	54.76	56	0.384	0.395	1.889	0.128
14	1948	154	153.95	153.83	55.81	57	0.363	0.369	1.827	0.113
15	1581	165	164.67	164.51	57.47	58	0.349	0.351	1.906	0.008
16	1317	176	175.83	175.60	55.41	54	0.315	0.307	1.886	-0.044
17	1066	187	186.71	186.70	53.56	52	0.287	0.281	1.668	0.086
>17	2908	NA	234.19	215.84	49.89	46	0.227	0.209	1.885	-0.088

Table 2: Analysis of risk-taking behaviour across different levels of the lagged standardised score differential

This table reports regression results linking the risk-taking behaviour of cricketers with the difference between the team score and the par score in 1207 one-day international cricket matches played between May 2005 and December 2014. We regress $StdevCh_i$ (the standard deviation of the change in the team's score relative to the par score for ball n for bin i) on $LagStDiff_i$ (the average lagged standardised difference between the team's score and the par score $((S_{n-1}-P_{n-1})/R_{n-1})$ for bin i). Panel A reports the estimation results from a linear regression while the results from the estimation of a non-linear logistic function are provided in Panel B. T-statistics are estimated using Huber-White consistent standard errors and are provided in parentheses while ** and *** indicate significance at the 5% and 1% levels respectively.

Panel A: Linear model results

$$StdevCh_i = \alpha_0 + \alpha_1 LagStDiff_i + \varepsilon_i$$

α_0	2.706 (80.06***)
α_1	-0.007 (-21.82***)
N	35
R^2	0.934
AIC	-11.41

Panel B: Non-linear model results

$$StdevCh_i = \beta_0 + \frac{\beta_1}{[1 + e^{-\beta_2(LagStDiff_i - \beta_3)}]} + \varepsilon_i$$

β_0	1.801 (34.72***)
β_1	2.211 (13.10***)
β_2	-0.020 (-7.30***)

β3	-36.44 (-4.66***)
N	35
Adjusted R^2	0.978
AIC	-47.46

Table 3: Testing the sensitivity of risk-taking behaviour to the resources remaining of the embedded option

This table reports regression results testing the risk-taking behaviour of cricketers for two subsamples. Low R (High R) represents those observations where the lagged level of resources remaining (R) prior to the observation ball was in the bottom (top) quartile of ranked observations in the total sample. We regress $StdevCh_i$ (the standard deviation of the change in the team's score relative to the par score for ball n for bin i) on $LagDiff_i$ (the average lagged difference between the team's score and the par score ($(S_{n-1}-P_{n-1})$) for bin i). T-statistics are estimated using Huber-White consistent standard errors and are provided in parentheses while *, ** and *** indicate significance at the 10%, 5% and 1% levels respectively.

$$StdevCh_i = \beta_0 + \frac{\beta_1}{[1+e^{-\beta_2(LagDiff_i-\beta_3)}]} + \varepsilon_i$$

	Low R	High R
β0	1.769 (13.54***)	2.084 (6.64***)
β1	2.576 (2.42***)	1.399 (1.24)
β2	-0.085 (-2.26**)	-0.065 (-0.98)
β3	-17.752 (-1.87*)	-9.427 (-0.58)
N	33	33
Adjusted R^2	0.887	0.626
AIC	1.20	10.01

Table 4: Testing the link between the average outcome from batsmen's actions across different levels of the lagged standardised score differential

This table reports regression results testing the relationship between the average outcomes from each ball bowled and the standardised score differential prior to the ball being bowled. We regress $ChScdiff_i$ (the average change in the team's score relative to the par score for ball n for bin i) on $LagStDiff_i$ (the average lagged standardised difference between the team's score and the par score $((S_{n-1}-P_{n-1})/R_{n-1})$ for bin i). T-statistics are estimated using Huber-White consistent standard errors and are provided in parentheses while ** and *** indicate significance at the 5% and 1% levels respectively.

$$ChScdiff_i = \beta_0 + \frac{\beta_1}{[1 + e^{-\beta_2(LagStDiff_i - \beta_3)}]} + \varepsilon_i$$

β_0	-0.164 (-4.44***)
β_1	0.243 (4.68***)
β_2	0.027 (2.29**)
β_3	-22.74 (-1.33)
N	35
Adjusted R^2	0.770
AIC	-104.47

Figure 1: Expected payoff from a binary option

This figure plots the expected payoff from a sporting contest for different levels of volatility and across a range of intrinsic values. Volatility is positively (negatively) related to the expected payoff from the option when the team chasing down the target score is behind, S<P, (ahead, S > P) of its par score at point *t* of the game.

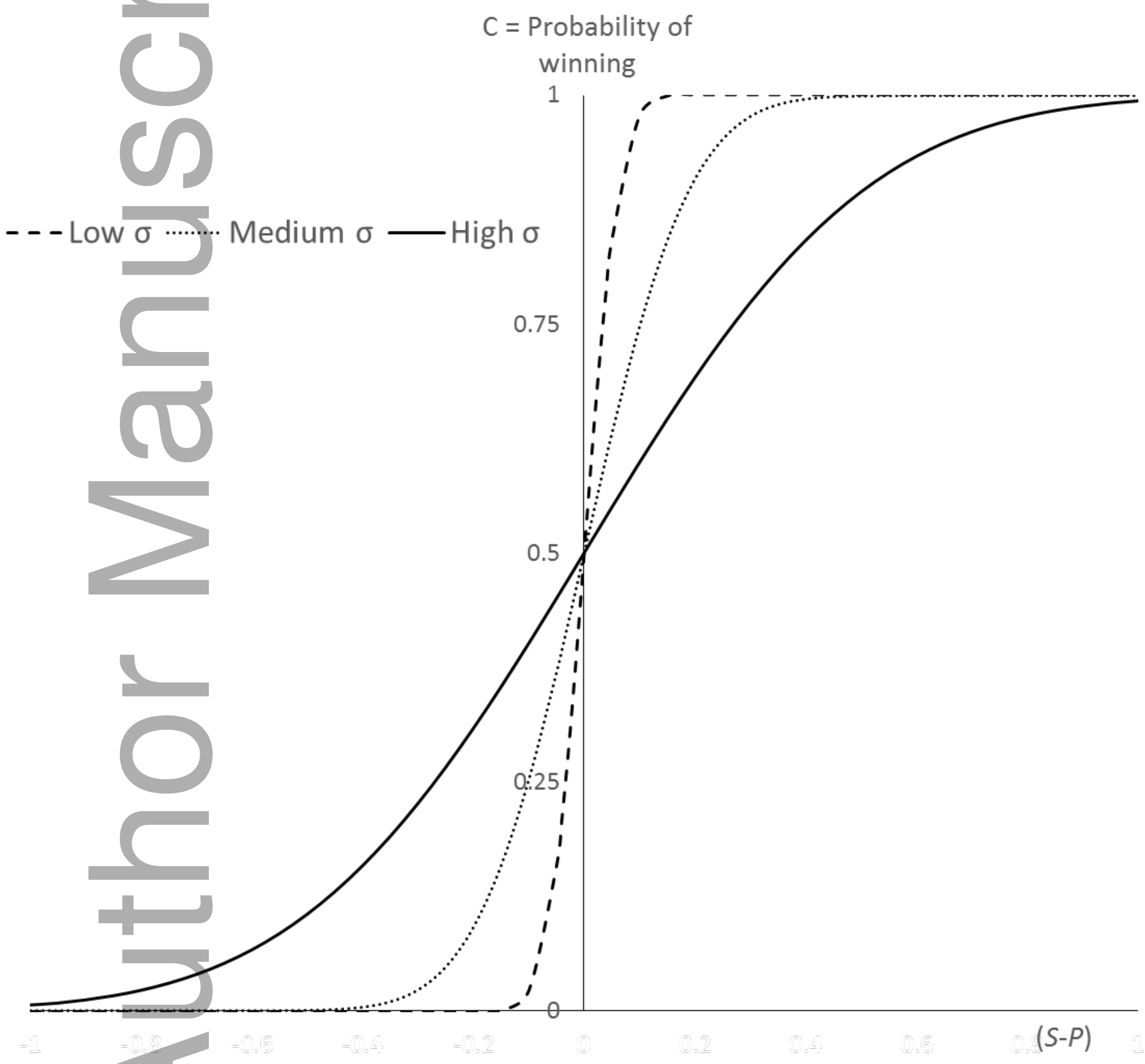

Figure 2: Option vega (ν) for values of (*S*−*P*)

This figure plots the sensitivity of a binary option's value to changes in volatility (the option's vega: ν) across values of (*S*−*P*). It shows that whilst vega is always positive (negative) when the option is in-the-money (out-of-the-money), it approaches zero as it gets deeper in or out of the money.

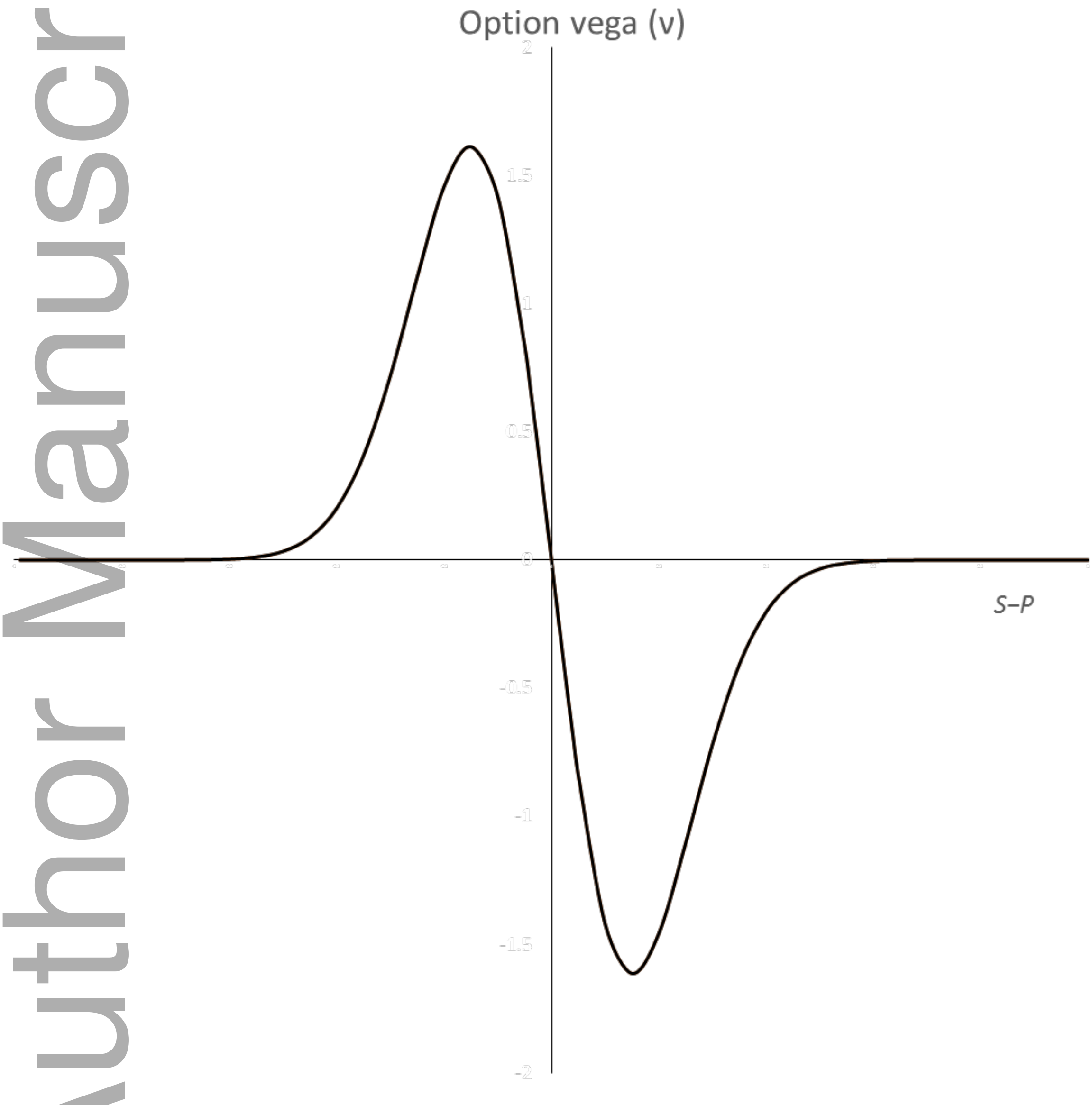

Figure 3: The relationship between risk-taking behaviour and the lagged standardised score differential of the embedded binary option

This figure plots the standard deviation of the change in the team score relative to the par score (*S*-*P*) across groups formed on the basis of the standardised difference between the chasing team's score and the par score prior to the delivery faced. Each group, except for the left-extreme and right-extreme groups, includes all observations across a standardised difference of 11 runs, with the central group capturing all observations with a standardised difference of between -5.5 and +5.5 standardised runs. The left-extreme and right-extreme groups are circled and consist of all observations with a lagged standardised run difference of less than -192.5 runs and greater than +192.5 runs respectively.

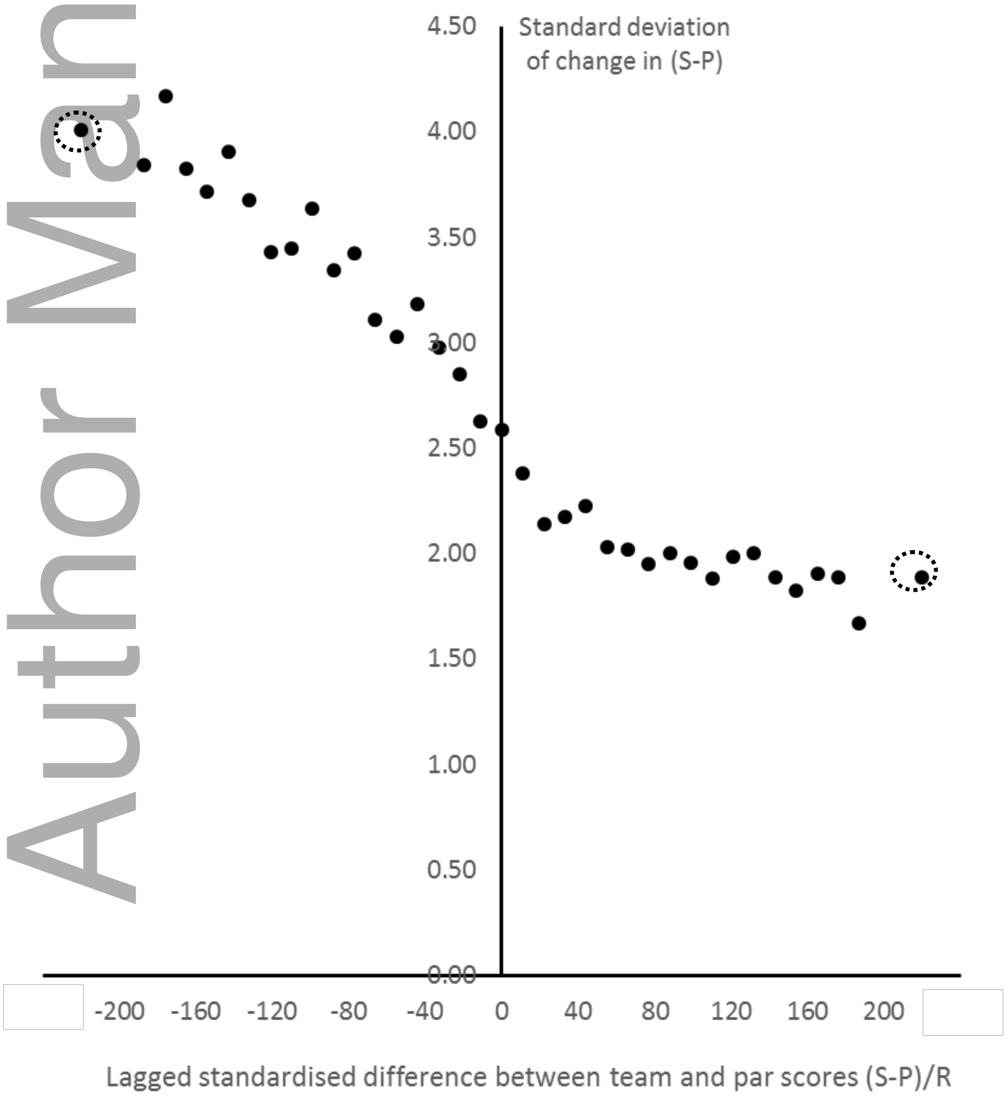

Figure 4: The relationship between the average outcome from each delivery and the lagged standardised score differential

This figure plots the average change in the team score relative to the par score (*S-P*) across groups formed on the basis of the standardised difference between the chasing team's score and the par score prior to the delivery faced. Each group, except for the left-extreme and right-extreme groups, includes all observations across a standardised difference of 11 runs, with the central group capturing all observations with a standardised difference of between -5.5 and +5.5 standardised runs. The left-extreme and right-extreme groups are circled and consist of all observations with a lagged standardised run difference of less than -192.5 runs and greater than +192.5 runs respectively.