



## OPEN Social post-error adaptations across four NBA basketball seasons

Ayala Denul<sup>1✉</sup>, Gilles Pourtois<sup>2</sup>, Tom Loeys<sup>3</sup> & Wim Notebaert<sup>1</sup>

Error monitoring, a crucial aspect of behavioral regulation, has been studied extensively in cognitive psychology and neuroscience. Lab studies often observe that people become more cautious after both own and others' errors. Moreover, social error monitoring research suggests that cooperation elicits stronger adaptations to others' errors than competition. However, these insights primarily stem from controlled reaction time tasks, limiting generalization to real-world social settings. To address this, we investigated whether basketball players become more cautious after missing compared to making shots, and whether these adaptations differ when the miss was by themselves, teammates or opponents. Meta-analyses of four NBA-seasons revealed increased caution in terms of shot distance and angle following missed compared to made shots, with the most pronounced effect after own, next teammates' and last opponents' errors. While controlling for rebound shots reduced the effects, the general pattern remained. Additional analyses also revealed a positive correlation between post-error caution and accuracy, suggesting post-error caution may serve to improve shooting accuracy. These findings not only extend cognitive theories from controlled settings to a real-world sport setting, but also provide a crucial understanding of athletes' social error responses thereby paving the way for research aimed at optimizing this aspect of performance.

**Keywords** Post-error caution, Performance monitoring, Social interaction, Cooperation vs. competition, Athlete behavior, Basketball game data analysis

In social interactions, adapting efficiently to one's own and others' errors is crucial<sup>1</sup>. Picture a dinner party where someone accidentally spills a glass of wine, a road trip where you take a wrong turn by mistake or a soccer match where your teammate misses a crucial penalty. These examples illustrate how adapting to errors, whether they are our own or others, is a fundamental skill in various aspects of life. For decades, error monitoring, or detecting and adapting to errors, has been a central focus in the fields of cognitive psychology and neuroscience. While extensive experimental research has provided us with a good understanding of error responses in controlled lab settings<sup>1,2</sup>, extending these theories and models to real-world social contexts remains a significant challenge. In the high-stakes arena of competitive sports, where every misstep can be costly<sup>3</sup>, understanding athletes' error responses becomes even more important. Do athletes become reckless or retreat to a cautious approach after an erroneous action? Moreover, is their adaptation different when the error is made by themselves, a teammate or an opponent? To answer these questions, we investigated social post-error adaptations in professional basketball games. Studying post-error adaptations in sports not only extends cognitive theories beyond controlled lab settings, but also holds significant promise for the fields of sport psychology and sport management.

Decades of cognitive psychology and neuroscience research have demonstrated that errors typically evoke two behavioral adaptations: post-error slowing, which entails slower reaction times after errors compared to correct responses, and post-error accuracy increase, which refers to a decreased probability of making an error following an erroneous action compared to a correct one<sup>2</sup>. Notably, post-error slowing has also been referred to as post-error cautiousness as heightened caution has been identified as the primary driving force behind this effect<sup>4,5</sup>. While considerable progress has been made in understanding how and why individuals adapt to their own errors<sup>1,2</sup>, recent attention has shifted to the responses following others' errors. Behavioral studies revealed similar adaptations following self-generated and others' errors in neutral contexts<sup>6</sup>. Moreover, research indicates that these adaptation effects depend on the social context of interactions. For instance, studies have shown more pronounced post-error slowing in a cooperative compared to a competitive context<sup>7,8</sup>.

Much of the current understanding on cooperative vs. competitive dynamics in social error monitoring stems from controlled reaction-time tasks. While these tasks offer valuable insights, their ability to capture the complexities of real-life social interactions might be limited, potentially restricting their generalizability<sup>9</sup>. Team sports, however, offer a prime example of such dynamics in real-life. In team sports, the inherent distinction

<sup>1</sup>Department of Experimental Psychology, Ghent University, Ghent, Belgium. <sup>2</sup>Department of Experimental Clinical and Health Psychology, Ghent University, Ghent, Belgium. <sup>3</sup>Department of Data-Analysis, Ghent University, Ghent, Belgium. ✉email: ayala.denul@ugent.be

between teammates and opponents provides a very relevant and concrete manifestation of cooperative vs. competitive relationships. Furthermore, despite the inherent unpredictability of the outcome of sporting events, they are governed by well-defined rules and outcomes, often resulting in rich datasets with precise measures. Exploring how athletes adapt to errors in sports thus presents a valuable opportunity to extend cognitive theories from highly controlled lab settings to a real-world social context. Moreover, given that athletes frequently make rapid decisions that can critically impact the outcome of the game<sup>10,11</sup>, understanding how athletes adapt to errors is crucial and could potentially help adjust and improve performance at both the individual and group level in team sports.

A specific team sport that offers a valuable framework for studying sequential effects such as post-error adaptations, is basketball. This is mainly due to its repetitive shot structure and ability to objectively determine the correctness of each attempt based on whether the ball eventually goes into the basket or not. As a result, numerous studies have previously analyzed basketball data to study the ‘hot-hand’ phenomenon, where players are believed to be more likely to score after a (streak of) successful shots<sup>12–16</sup>. While this phenomenon is related to success, its counterpart, the ‘cold-hand’ relates to misses. Typically, research on the ‘hot/cold-hand’ phenomenon focuses on the likelihood of making the next shot given the outcome on the previous shot. Some studies have also explored statistics related to the shooting strategy, such as shot distance and type. Both Attali<sup>16</sup> and Csapo, et al.<sup>15</sup> found that players tend to take shots from closer distances during streaks of missed shots (where the ball did not go through the hoop and no points were scored) compared to streaks of made shots (where the ball successfully went through the hoop and points were scored). Additionally, Csapo, et al.<sup>15</sup> and Neiman and Loewenstein<sup>14</sup> demonstrated that players opt for less risky shots following missed compared to made shots. These findings align with traditional error-monitoring research, providing evidence for post-error cautiousness following basketball players’ own errors.

Despite the extensive research on sequential effects in basketball, a notable limitation lies in the exclusive focus on the effects following players’ own errors which neglects the inherent social nature of team sports. However, as a team sport with relatively small teams, basketball presents a unique opportunity to explore adaptations following errors not only by oneself, but also by teammates and opponents. This team characteristic thus offers a unique context for studying social post-error adaptations in sports. While Neiman and Loewenstein<sup>14</sup> briefly explored the impact of players’ missed shots on their own performance and that of teammates, their analysis of shooting behavior was limited to the shooting player only. Therefore, we sought to extend previous basketball data analyses by studying the impact of errors by teammates and opponents on shooting behavior, on top of the impact of players’ own errors.

In this study, we used online-available NBA (National Basketball Association) data to investigate whether players adapt differently after missed vs. made attempts by themselves, teammates, or opponents. Consistent with previous research on the ‘hot/cold hand’ phenomenon, we used the outcome of each attempt as objective measure of success or failure. Both angle and distance were used as indicators of shot caution as closer shots or shots from smaller angles are often considered as easier and more cautious given the higher likelihood of scoring from these positions, which we also confirmed in our data. Drawing from previous research comparing self-generated and observed errors, we expected reduced post-error cautiousness following others’ compared to own errors<sup>6,7</sup>. Crucially, we hypothesized increased post-error cautiousness following errors by a teammate compared to an opponent, mirroring the effect of cooperation vs. competition manipulations<sup>7,8</sup>. Overall, we predicted a more cautious shooting strategy, in terms of shot distance and angle, after errors compared to successful attempts with the strongest effect following own, next teammates’ and last opponents’ errors.

In addition to exploring the dynamics of cooperation and competition in players’ error responses, we also sought to gain insight into their likely functional role. Specifically, our secondary objectives were to determine the stability of these error responses, the convergence between the adaptations to one’s own, teammates and opponents’ errors, and assess whether post-error cautiousness or recklessness results in improved accuracy. While a cautious shooting strategy is typically linked to higher success rates, similar to slower reaction times in lab studies, the relationship between post-error slowing and post-error accuracy has long been a topic of debate<sup>1</sup>. Building on research by Van der Borgh, Desmet and Notebaert<sup>17</sup> indicating that strategy changes improve post-error performance in a more ecologically valid task, we aimed to explore this in a real-life sport context.

## Methods

The data analyzed in this study comes from a third-party source (<http://www.basketballgeek.com/data/>), and was accessed for download on 18th October, 2023. This dataset includes open-source data from four NBA seasons, and was fully anonymized before analysis. This dataset was used as it includes detailed information on each shot, including outcome and spatial location in  $1 \times 1 \text{ ft}^2$  ( $0.3048 \times 0.3048 \text{ m}^2$  resolution). Since this study involved the analysis of online available, open-source data, no ethical approval was required. All anonymized and processed datafiles are accessible via OSF (<https://osf.io/vcj3b/>).

## Dataset

For each shot attempt, we computed the distance (in meters) and angle (in degrees) relative to the basket using the spatial information associated with each attempt. To calculate the distance between the point of the shot and the basketball hoop, we applied the Euclidean distance formula derived from the Pythagorean theorem. If the shot coordinates are represented by  $(x_{shot}, y_{shot})$  and the coordinates of the basket as  $(x_{basket}, y_{basket})$ , the distance is computed as:

$$d = \sqrt{(x_{shot} - x_{basket})^2 + (y_{shot} - y_{basket})^2}$$

Season	Games included	Games excluded	Players included	Players excluded	Shots without location information	Total shots analyzed
2006–2007	1149	0	410	47	605	157 967
2007–2008	1183	0	372	78	271	154 715
2008–2009	1174	2	362	82	1203	145 418
2009–2010	1209	6	367	73	1192	155 974

**Table 1.** Information on the data in-/excluded in the analysis of each season.

Season	Outcome previous shot	Social context consecutive shots		
		Within player	Within team	Between team
2006–2007	Success	3 406	11 127	58 679
	Error	6 804	27 390	50 561
2007–2008	Success	3 225	10 449	58 119
	Error	6 617	25 952	50 353
2008–2009	Success	3 136	9 781	54 591
	Error	6 509	24 491	46 910
2009–2010	Success	3 253	10 600	59 172
	Error	6 526	26 295	50 128

**Table 2.** Number of shots analyzed in each season by outcome of the previous shot and social context of consecutive shots.

The angle relative to the basket was defined as the angle between the vertical line passing through the center of the hoop and the line connecting the shot location to the center of the hoop. To calculate this angle, we used the inverse tangent of the ratio between the horizontal and vertical difference in location of the shot and center of the basket. The result of the inverse tangent, initially in radians, was then converted to degrees for easier interpretation. If the shot coordinates are represented by  $(x_{\text{shot}}, y_{\text{shot}})$  and the coordinates of the basket as  $(x_{\text{basket}}, y_{\text{basket}})$ , the angle is computed as:

$$\theta = \tan^{-1} \frac{|x_{\text{shot}} - x_{\text{basket}}|}{|y_{\text{shot}} - y_{\text{basket}}|}$$

The absolute value of the difference in the x- and y-coordinates ensures that the angle is always between 0° and 90°, with 0° indicating positions directly in front of the basket and 90° corresponding to positions on the right or left of the basket. This allowed for a consistent analysis of the angle relative to the basket regardless of whether the shot was taken from the left or right side of the court. Next, we categorized the outcome of the preceding shot as either successful (made), when the ball successfully went through the hoop and points were scored, or erroneous (missed), when the ball did not go in the hoop and no points were scored. Lastly, we considered the agent of shot N-1 and the agent of shot N. This allowed us to categorize the social context of consecutive shots as either within player (where both shots are taken by the same player), within team (where the previous shot was taken by a teammate) or between team (where the previous shot was taken by an opponent).

We excluded data from eight games due to either empty files or missing spatial location (two games from the 2008–2009 season and six from the 2009–2010 season). Additionally, the first shot in each period was excluded to avoid considering a shot from a previous game or period as the preceding shot. We also excluded shots if the player on shot N or shot N-1 switched teams throughout a season as the teammate vs. opponent distinction could be ambiguous in such cases. Shots were also excluded if the player on shot N or shot N-1 took less than 10 shots in a season or if no location was recorded for a shot. This accounted for less than 2% of the remaining shots in each season. These exclusions were applied after classifying the social context and outcome of the previous shot to prevent earlier shots from being considered as the immediately preceding shot. After preprocessing, each season included, on average, 1 179 games, shots by 378 players and an average total of 153 519 shots. Table 1 provides a detailed overview of the amount of games, players and shots in-/excluded in the analysis of each season. Table 2 presents an overview of the shots analyzed in each season by the outcome of the previous shot and social context of consecutive shots.

### Data analysis

Statistical analyses were conducted using R Statistical Software, version 4.3.1. Our main analysis focused on post-error cautiousness in terms of distance and angle. This was followed by a control analysis aimed at potentially filtering out immediate rebounds. Lastly, we studied the correlation between players' post-error cautiousness and post-error accuracy, as well as the reliability and convergence of players' post-error responses. The analyses were structured in two steps. First, data from four seasons were analyzed separately to account for changes in team composition across seasons. Next, the results from all seasons were entered into meta-analyses. The choice of meta-analyses over a single mixed effects model offers both methodological and applied advantages. It provides

great flexibility in modeling between-season heterogeneity. By independently estimating and visualizing each season's coefficient, it enhances interpretability and simplifies the identification of outliers or unusual patterns in specific seasons. Importantly, this approach naturally aligns with the structure of sports, where each season is often considered as a distinct entity similar to separate experiments in cognitive control research. The large sample sizes per season allowed the season-level analyses, which were then integrated in meta-analyses. For the meta-analyses, we fitted fixed-effect models using the R-package metafor, version 4.4-0<sup>18</sup>. To address the issue of multiple comparisons arising from conducting two tests of post-error cautiousness (distance and angle) within each social context, a Bonferroni correction was applied. Consequently, all statistical analyses were performed at the 2.5% level of significance. To validate whether distance and angle to the basket are reliable indicators of shot caution, we first analyzed whether shots taken from shorter distances or narrow angles are indeed more likely to be successful compared to long distance or wide shot. To analyze this, we fitted logistic regression models for distance and angle. For the analysis of post-error cautiousness, we fitted linear mixed models to test whether players become more cautious after errors compared to successful shots (see Eqs. 1 and 2). Specifically, in line with post-error slowing literature, we compared the mean distance and angle after successful versus erroneous shots. Separate models were fitted for distance and angle on shot N as dependent variables. The outcome of the preceding shot was included as a predictor variable ( $Outcome_{N-1}$ ), with successful shots as reference level. In these models, the intercept represents the mean distance or angle after a successful shot ( $\beta_0$ ). The regression coefficient for the outcome of the previous shot then indicates the average difference in distance (meters) or angle (degrees) on shot N if the previous shot was erroneous compared to successful ( $\beta_1$ ). These models were fitted for each social context (own, teammates', and opponents' errors) separately, resulting in a total of six separate models. To account for variability across games, team strategies and individual players, random intercepts were included for game ( $u_{Game_i}$ ), team nested within game ( $u_{Team_j|i}$ ) and player nested within team and game ( $u_{Player_{k|j,i}}$ ). Finally, a residual variability term was included ( $\epsilon_{i,j,k}$ ) to capture the residual variability for shot N by player k in team j in game i.

$$Distance_{i,j,k} = \beta_0 + \beta_1 * Outcome_{N-1} + u_{Game_i} + u_{Team_j|i} + u_{Player_{k|j,i}} + \epsilon_{i,j,k} \quad (1)$$

$$Angle_{i,j,k} = \beta_0 + \beta_1 * Outcome_{N-1} + u_{Game_i} + u_{Team_j|i} + u_{Player_{k|j,i}} + \epsilon_{i,j,k} \quad (2)$$

In a control analysis, we addressed potential confounding rebound shots in the within player and within team context. Specifically, in these two contexts it is possible to immediately take a shot after obtaining the rebound. These offensive rebounds typically occur in locations closer to the basket. When this rebound is immediately followed by a shot, this can artificially create a post-error caution pattern in the within team or within player context. To control for this, we excluded shots that followed an offensive rebound within one second both in the within player and within team context. This one-second threshold was chosen to isolate shots with no intervening actions between the rebound and subsequent shot. Given the absence of data on dribbling or passing actions following a rebound, extending the timeframe would risk excluding shots with intervening actions. On average, we excluded 18.13% of shots following a miss in the within player context (2006–2007 15.49%, 2007–2008 14.21%, 2008–2009 15.26%, 2009–2010 27.55%) and 13.00% in the within team context (2006–2007 10.62%, 2007–2008 9.17%, 2008–2009 9.42%, 2009–2010 22.79%). Subsequently, we performed the same analyses.

Next, we assessed the correlation between post-error cautiousness and post-error accuracy by computing players' scores for both measures. Post-error cautiousness scores were calculated as the difference between the mean post-correct and mean post-error distance or angle for each player. Post-error accuracy scores were calculated as the difference between post-error and post-correct accuracy for each player. A positive correlation would thus indicate that players who become more cautious also become more accurate following errors, and vice versa. The correlation between both types of post-error cautiousness and post-error accuracy was analyzed for each social context separately, resulting in six correlational analyses. T-tests were used to analyze the correlations.

Using players' post-error scores, we also assessed the reliability of their post-error responses to determine whether this behavior exhibits a stable trait-like quality or displays high variability. To this end, we analyzed the autocorrelation of players' post-error tendencies across two consecutive seasons within each social context separately. Finally, we assessed the convergence of players' post-error cautiousness scores in the three social contexts through pairwise correlations.

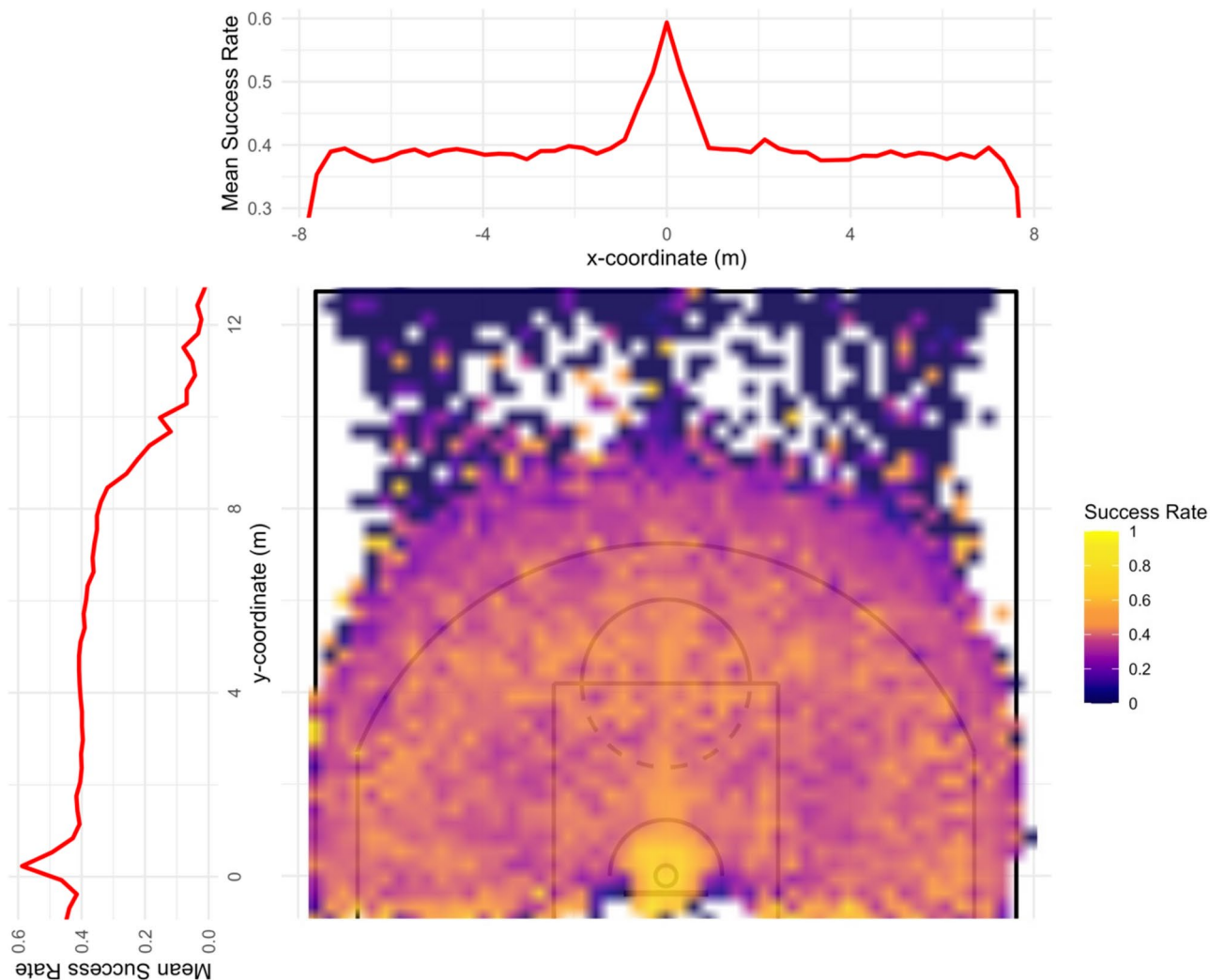
## Results

### Accuracy by distance and angle

The meta-analysis of the logistic regressions revealed a significant ( $p < 0.001$ ) log-odds of success of -0.13 for distance and -0.01 for angle. Exponentiating these coefficients yielded odds ratios of 0.87 and 0.99, indicating that increasing the distance by 1 m (1 unit of measurement) or angle by 10 degrees (10 units of measurement) decreased the odds of success by 13.0% and 9.6%, respectively. These findings thus indicate a significantly higher chance of scoring from a closer distance or smaller angle, thereby confirming that distance and angle serve as reliable indicators of shot caution. Figure 1 depicts the success rates across the basketball court aggregated over the four seasons.

### Post-error cautiousness

The meta-analysis of post-error cautiousness revealed a significant reduction in both distance and angle across all social contexts (see Fig. 2). The most pronounced effect was found for the within player context, with a mean reduction in distance of 1.47 m (97.5% CI [-1.54, -1.40],  $p < 0.001$ ) and 7.33 degrees in angle (97.5% CI [-8.05, -6.61],  $p < 0.001$ ) after an error compared to a successful shot. This was followed by the within team context,



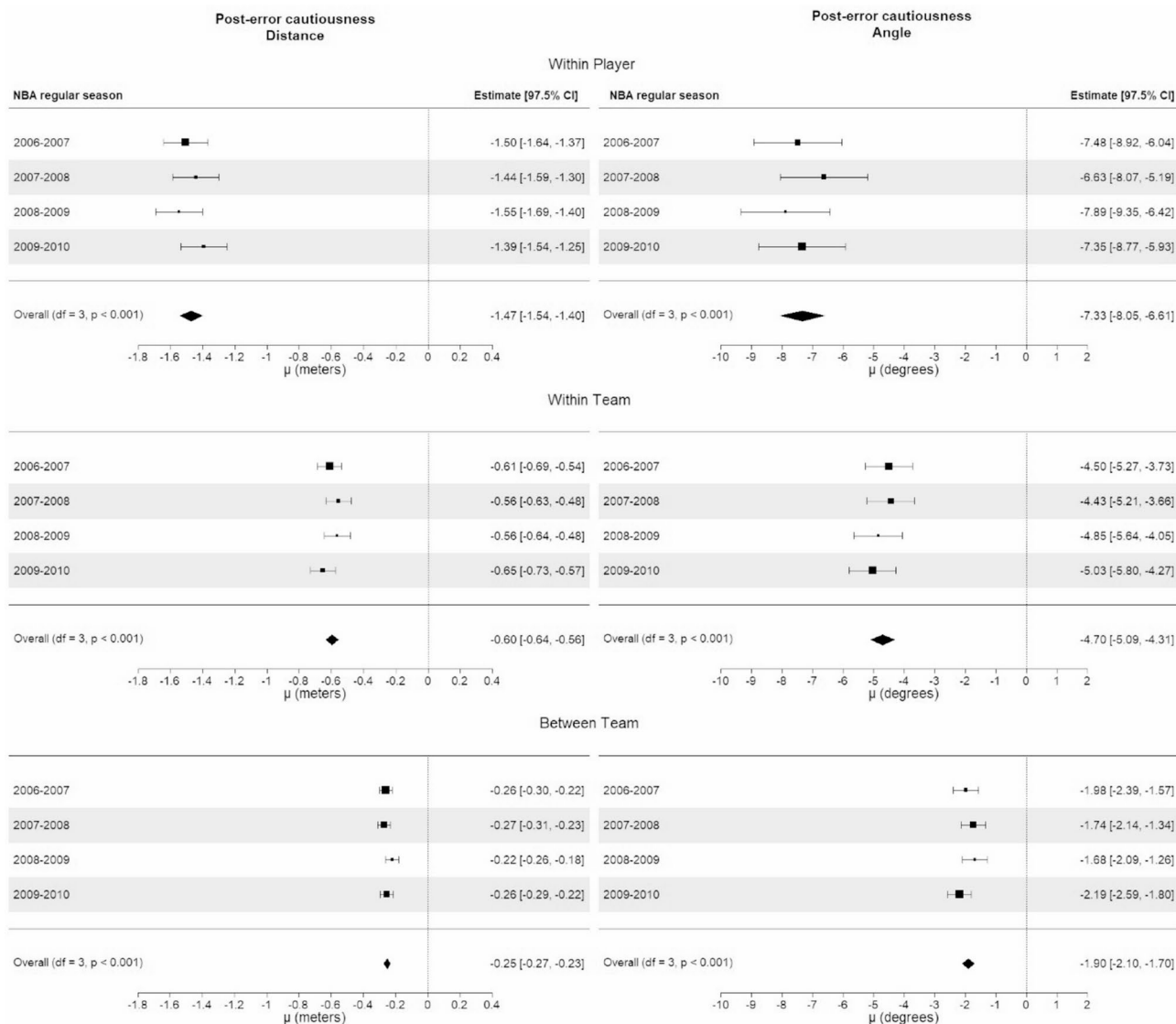
**Fig. 1.** Proportion of successful shots aggregated across the four seasons. Note. Heatmap showing the proportion of successful shots across the basketball court, with mean success rates displayed on the x- and y-axes. Locations where only one shot was taken over all seasons were excluded.

with a mean reduction of 0.60 m in distance (97.5% CI [-0.64, -0.56],  $p < 0.001$ ) and 4.70 degrees in angle (97.5% CI [-5.09, -4.31],  $p < 0.001$ ). The smallest effect was found in the between team context with a mean reduction of 0.25 m in distance (97.5% CI [-0.27, -0.23],  $p < 0.001$ ) and 1.90 degrees in angle (97.5% CI [-2.10, -1.70],  $p < 0.001$ ).

In these models, the variance explained by the random intercept at the player level was notably higher compared to the variance explained by the random intercepts at the team or game level. For distance, the player level accounted, on average, for 15.69% of the total variance in the within player models, 21.40% in the within team models and 16.33% in the between team models. When considering angle, it accounted for, on average, 7.32% of the total variance in the within player models, 8.45% in the within team models and 5.92% in the between team models. In the distance models, the variance at the team and game levels contributed less than 1% of the total variance. Similarly, in the angle models, the variance associated with the team level contributed less than 1% and the variance associated with the game level contributed less than 4% of the total variance. A detailed overview of all results per model and per season can be found in the supplementary files (S1).

### Control analysis

After excluding immediate rebounds, we performed the same analyses for the within player and within team specifically. The meta-analysis revealed a reduced post-error cautiousness effect in terms of distance and angle in both social contexts compared to our previous analysis. The most pronounced effect was still found for the within player context, with a mean reduction in distance of 1.07 m (97.5% CI [-1.14, -0.99],  $p < 0.001$ ) and 4.11 degrees in angle (97.5% CI [-4.86, -3.35],  $p < 0.001$ ) after an error compared to a successful shot. In the within team context, we found a mean reduction of 0.28 m in distance (97.5% CI [-0.32, -0.24],  $p < 0.001$ ) and 2.14 degrees in angle (97.5% CI [-2.54, -1.74],  $p < 0.001$ ). A detailed overview of all results per model and per season can be found in the supplementary files (S2).



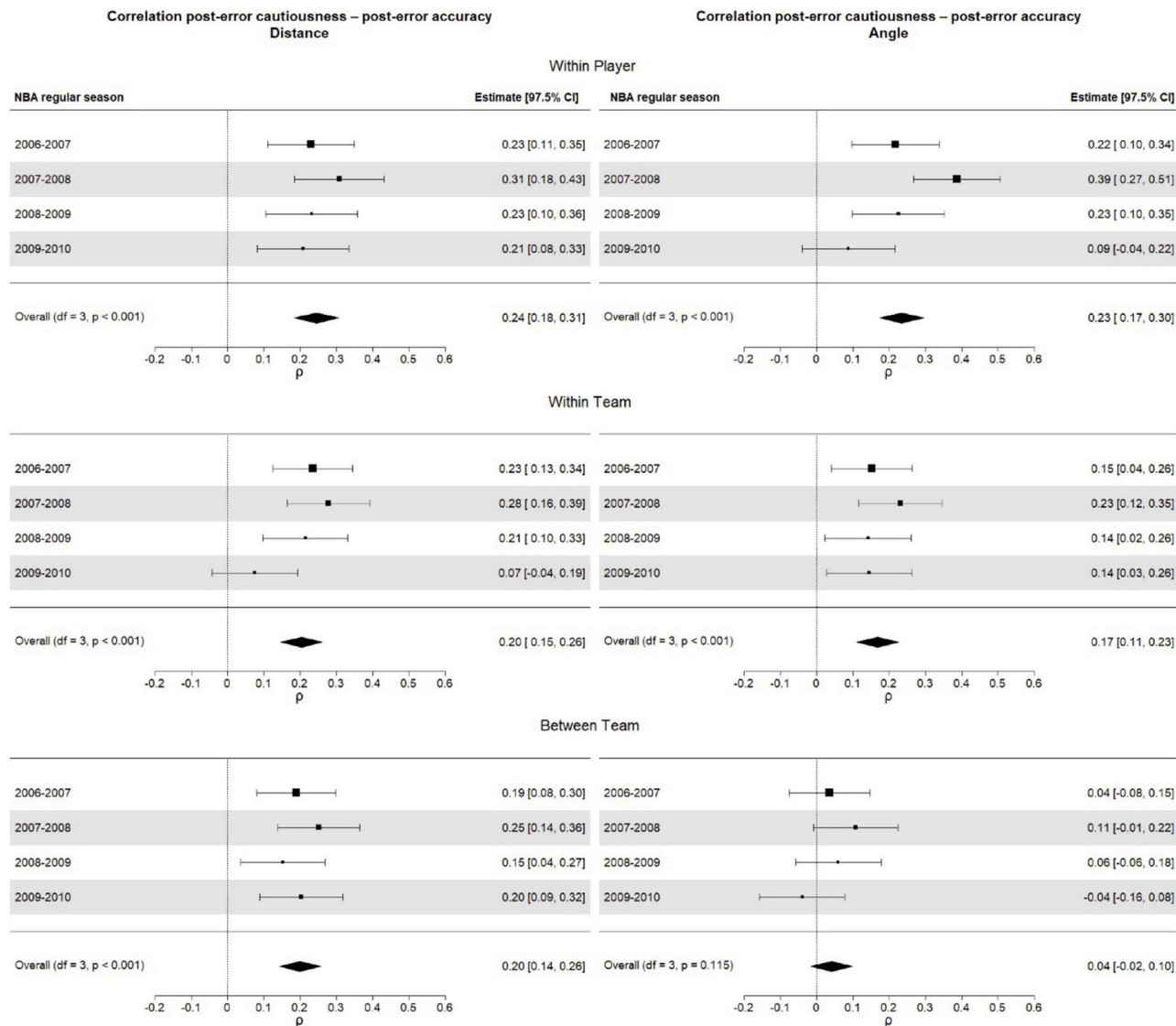
**Fig. 2.** Results (meta-analysis across four NBA seasons) for post-error cautiousness. Note. Left: results meta-analyses for distance, right: results meta-analyses for angle. Top: within player results, middle: within team results, bottom: between team results.  $\mu$  = effect size, negative values indicate post-error distance or angle reduction (post-error caution), positive values indicate post-error distance or angle increase (post-error recklessness). The size of the squares reflects the weight of the study, determined by its precision which depends on sample size and standard errors. The width of the diamond represents the confidence interval for the pooled estimate.

### Post-error accuracy

We found a significant positive correlation between post-error cautiousness, in terms of both distance and angle, and post-error accuracy in the within player context (distance  $\rho=0.24$ , 97.5% CI [0.18, 0.31],  $p<0.001$ ; angle  $\rho=0.23$ , 97.5% CI [0.17, 0.30],  $p<0.001$ ) and the within team context (distance  $\rho=0.20$ , 97.5% CI [0.15, 0.26],  $p<0.001$ ; angle  $\rho=0.17$ , 97.5% CI [0.11, 0.23],  $p<0.001$ ). In the between team context, only post-error cautiousness in terms of distance was significantly correlated with post-error accuracy ( $\rho=0.20$ , 97.5% CI [0.14, 0.26],  $p<0.001$ ), whereas no significant correlation was found for post-error cautiousness in terms of angle ( $\rho=0.04$ , 97.5% CI [-0.02, 0.10],  $p=0.115$ ). Figure 3 provides an overview of these results. All effect sizes remained unchanged when controlling for immediate rebounds in the within player and within team context, except a small increase was observed in the correlation between post-error cautiousness, measured by angle, and post-error accuracy in the within team context ( $\rho=0.19$ , 97.5% CI [0.13, 0.24],  $p<0.001$ ).

### Exploration of the impact of previous shot outcome on points scored

As exploratory analysis, we calculated the average points scored (0, 2, or 3) on the subsequent shot across all players and all seasons, depending on the outcome of the previous shot. This helps to evaluate whether the change in shooting strategy based on the previous shot's outcome leads to an increase in the expected number of



**Fig. 3.** Results (meta-analysis across four NBA seasons) for the correlation between post-error cautiousness and post-error accuracy. Note. Left: results meta-analyses post-error cautiousness in terms of distance, right: results meta-analyses for post-error cautiousness in terms of angle. Top: within player results, middle: within team results, bottom: between team results.  $\rho$  = correlation coefficient. The size of the squares reflects the weight of the study, determined by its precision which depends on sample size and standard errors. The width of the diamond represents the confidence interval for the pooled estimate.

points scored. To ensure sufficient data points in each score category, the data of all players, teams and seasons were combined for these calculations.

In the within player context, the expected score after a made shot was 0.99 points and the expected score after a miss was 1.04 points. In the within team context, the expected score after both a made and missed shot was 1.03 points. In the between team context, the expected score after a made shot was 0.96 and the expected score after a missed shot was 1.01 points. These differences indicated that a missed shot only slightly increases the expected points on the next shot in both the within player and between team contexts, whereas no difference is observed in the within team context. Full details on these calculations, including equations and contingency tables, are available in supplementary material S3.

### Reliability and convergence of players' post-error responses

To assess the reliability of players' error response, we analyzed the autocorrelation of players' post-error cautiousness scores over consecutive seasons within each social context separately. T-tests revealed a significant positive correlation for cautiousness in terms of distance in all three social contexts ( $\rho_{\text{within player}} = 0.13$ ,  $\rho_{\text{within team}} = 0.29$ ,  $\rho_{\text{between team}} = 0.25$ ; all  $p < 0.001$ ), as well as for cautiousness in terms of angle in the within player ( $p = 0.11$ ;  $p = 0.003$ ) and within team contexts ( $\rho = 0.25$ ;  $p < 0.001$ ). No significant correlation was found between seasons for cautiousness in terms of angle in the between team context ( $\rho = 0.06$ ;  $p = 0.069$ ).

Lastly, we analyzed the correlation of players' post-error adaptation scores across the three contexts to assess the convergence of these tendencies. For distance, we found a significant positive correlation between players' adaptation to their own and teammates' errors ( $\rho = 0.15$ , 97.5% CI [0.09, 0.21],  $p < 0.001$ ). However, we found a significant negative correlation between players' adaptation to opponents' and both their own ( $\rho = -0.08$ , 97.5% CI [-0.14, -0.02],  $p = 0.005$ ) and teammates' errors ( $\rho = -0.13$ , 97.5% CI [-0.19, -0.07],  $p < 0.001$ ). When considering cautiousness in terms of angle, a significant positive correlation was found between players' response to their own and teammates' errors ( $\rho = 0.18$ , 97.5% CI [0.11, 0.24],  $p < 0.001$ ). Unlike the findings for distance, no significant correlation was found between players' adaptation in angle to opponents' and both their own ( $\rho = 0.02$ , 97.5% CI [-0.04, 0.09],  $p = 0.456$ ) and teammates' errors ( $\rho = -0.06$ , 97.5% CI [-0.12, 0.00],  $p = 0.030$ ).

## Discussion

In this study, we analyzed a large and rich existing dataset from four NBA regular seasons to scrutinize post-error adaptations in a sport setting where swift and dynamic interactions among players are crucial to performance and success, namely basketball. Our results reveal for the first time that post-error cautiousness strongly varies with the social game context, as shown by the most pronounced cautiousness observed following players' own errors, next teammates' errors and last opponents' errors. Moreover, when excluding immediate rebound shots, the difference between own and teammates' errors decreased, yet the general pattern between these two contexts persisted, showing that these immediate rebound shots could only partially explain the observed effects. Further, we found a positive correlation between post-error adaptations across seasons which indicates a certain degree of stability in players' post-error responses over time. Additionally, we found a positive correlation between players' responses to errors by themselves and teammates, while a negative or non-significant correlation was found between the response to opponents' errors and errors by oneself or teammates. This implies that players who become more cautious following their own errors also tend to exhibit increased caution after teammates' errors, but show a more reckless response after opponents' errors, and vice versa. Lastly, our analysis revealed a positive correlation between post-error cautiousness and post-error accuracy, suggesting that this cautious response may help improve shooting accuracy after an error.

Our study advances previous research on the 'hot/cold hand' in sports by examining the impact of teammates' and opponents' errors, on top of the impact of one's own errors, thereby offering valuable insights into social error monitoring in sports. While Neiman and Loewenstein<sup>14</sup> briefly explored the impact of players' errors on the performance of teammates, our analysis offers a more comprehensive investigation by considering teammates' and opponents' errors and their effect on shooting behavior instead of performance. Moreover, we include a control analysis that specifically excludes immediate rebound shots, enabling us to isolate behavior independent of immediate rebound effects. Our findings regarding players' responses to their own errors are consistent with previous game data analyses showing a tendency towards a more cautious shooting strategy following one's own missed attempts compared to successful shots<sup>14-16</sup>. Importantly, our study also reveals heightened caution, albeit to a lesser extent, following errors by teammates, along with a minimal effect following opponents' errors. In contrast to previous hot/cold hand research, our study focuses on individual made or missed shots rather than streaks<sup>13-15</sup>. This approach closely aligns with research on social post-error slowing in competitive versus cooperative settings<sup>7,8</sup>. Analyzing streaks while accounting for social context would substantially reduce the number of datapoints, rendering our analyses infeasible. However, this represents a notable limitation of our study.

Our results can also be interpreted in terms of a win-stay lose-shift strategy. Since we only compare average distance/angle of shots following misses and shots following hits, we cannot disentangle what happens after a hit and what happens after a miss. Presumably, players become less cautious after a hit and more cautious after a miss but the results might entirely be caused by players becoming more cautious after errors in line with a win-stay lose shift strategy. Note that a win-stay lose-shift strategy is typically demonstrated in sequential gambling tasks like the Iowa gambling task<sup>19</sup>, but it has also been demonstrated in football strategies<sup>20</sup>. Further controlled lab studies are required to test whether players (equally) adapt after hits and misses.

When analyzing game data, numerous uncontrolled factors come into play, making it challenging to pinpoint the exact cause of the observed effects. First, using this dataset, it is difficult to determine the exact level at which the adaptations occurred. Since data on every pass and dribble is unavailable, there may have been additional adjustments beyond the changes in shooting behavior. For example, more cautious shots following errors could have been preceded by riskier passes or dribbling actions. As a result, a key limitation of this study is that it is impossible to determine whether players exhibited greater caution in their overall gameplay or only in their shooting behavior. Second, previous research suggests that additional changes beyond players' shooting strategy might contribute to these effects. For example, changes in the instructions or behavior of the coach after missed shots could influence players' behavior. Research by Attali<sup>16</sup> supports this idea, indicating that coaches also respond to streaks of made vs. missed shots, with a lower likelihood of replacing a player during a 'hot streak'. It is plausible that coaches provide more assertive instructions when a player misses his own shot compared to when a teammate misses. Additionally, teammates or opponents may behave according to the hot-hand belief, favoring passes to a perceived 'hot' teammate or increasing defensive pressure on these players<sup>21</sup>. Players might also generalize this belief to some extent to a player's teammates thereby causing a similar, but reduced, effect following teammates' errors. Moreover, several psychological mechanisms within the shooting player or the team may underlie the observed effects. Even in the pioneering study by Gilovich, Vallone and Tversky<sup>13</sup>, player confidence was noted as a potential factor influencing streaks of made or missed shots. Additionally, factors such as perfectionism or collective collapse, which are common in sports<sup>3,22</sup>, could also explain the observed effects following own and teammates' errors. However, the inability to precisely identify the specific causes underlying the effects remains a limitation inherent to the analysis of game data.

Beyond the factors discussed, it is important to also consider the potential role of regression to the mean in explaining some of the observed effects. This is particularly relevant given that success rate increased with closer shot distance and angle (Fig. 1), suggesting that errors occur from positions further away than successful attempts. While we cannot completely rule out regression to the mean as a contributing factor, we would expect this statistical artefact to be consistent across the three contexts (own errors, teammates' errors, and opponents' errors). However, the observed differences across these contexts make it unlikely that regression to the mean alone fully explains the observed pattern. This contrasts with previous research on the hot hand which only focuses on the effect following players' own success and errors<sup>13,14,15</sup>. In those studies, ruling out regression to the mean is even more challenging without comparing the effects to these other contexts. However, in light of this, our findings should be interpreted with caution, recognizing that both adaptive behavior and statistical factors, such as regression to the mean, could be influencing the observed effect.

Despite the uncertainty surrounding the precise cause of the observed effects, our findings align with controlled behavioral studies on social error monitoring suggesting the potential involvement of players' adaptive control processes. First, previous behavioral studies consistently demonstrated greater post-error slowing following one's own compared to others' errors<sup>6,7,23</sup>. In line with this, we observed the most pronounced post-error cautiousness effect when the error was by a player himself, compared to by a teammate or opponent. Additionally, the difference in the magnitude of the effect following teammates' and opponents' errors mirrors findings on the impact of cooperation vs. competition on post-error slowing<sup>7,8</sup>. When excluding immediate rebound shots, the effect of errors by oneself and teammates decreases but the general pattern remains. In contrast, the difference in how errors by teammates compared to errors by opponents impact players, decreases. However, the negative or absent correlation between adaptations following opponents' errors and both own and teammates' errors suggests the involvement of different processes following opponents' errors. Conversely, the positive correlation between adaptations after own errors and teammates' errors suggests that shared processes are at play. Lastly, our results also indicate a certain level of stability over time, further supporting the notion that the observed effects are at least partially driven by internal control processes of the shooting player.

A potential mechanism driving these effects could be the affective value associated with own, teammates' and opponents' errors. In the context of observed errors, previous studies have proposed that post-error adaptations could be driven by the motivational significance of errors, with teammates' errors being perceived negatively or goal obstructive, and opponents' errors possibly even as positive, goal conducive events<sup>23</sup>. This interpretation can be integrated with the affective interpretation of post-error adaptations in individual task settings<sup>24</sup>. In this setting, it has been suggested that the negative affective evaluation associated with one's own errors triggers the adaptive changes, rather than the error itself. While the affective evaluation of others' errors has not yet been explored directly, these two interpretations closely align and can be combined to potentially explain the observed pattern in the post-error cautiousness effect. Specifically, we suggest that the negative affective evaluation of errors could follow the same pattern, with own errors being evaluated as the most negative and opponents' errors as the least negative. Importantly, the difference in affective value of errors by cooperators versus competitors is unlikely to be perfectly asymmetrical. Specifically, in sports like basketball, there is no perfect equivalence between the value of success by one's own team and errors of the opposing team. Scoring by oneself or a teammate is a positive event that directly leads to points for the team, while an opponent's missed shot is also a positive event but does not result in a loss of points for that team. Furthermore, existing studies on evaluative processing of actions reveal a pronounced asymmetry between errors, which are clearly perceived as negative, and correct actions, which are not always systematically perceived as positive or rewarding<sup>25</sup>. Hence, the negative value of an error is stronger in terms of affect than the rewarding value of a correct action. This is compatible with the "losses loom larger than gains" assumption<sup>26</sup>. As such, it is unlikely that an opponent's error is equivalent in terms of affect to a successful action by oneself or a teammate. This likely explains why the effect observed following opponents' errors is smaller, rather than entirely opposite to that following teammates' errors. Future studies could compare the affective evaluation of these errors directly to potentially uncover the mechanisms underlying these effects.

For the sports community, a crucial question is whether this behavior also leads to improved performance or not. While it may seem intuitive that reducing shot distance or angle after errors would enhance post-error shooting accuracy, the adaptive nature of post-error cautiousness has long been a subject of debate due to observed dissociations between post-error cautiousness and accuracy<sup>1</sup>. Our findings shed light on this association in the context of basketball, revealing a positive correlation between post-error cautiousness and accuracy. This aligns with research by Van der Borgh, Desmet and Notebaert<sup>17</sup>, who demonstrated that strategy changes can improve performance after errors in a more ecologically valid mental arithmetic task. These insights hold significant relevance for the world of sport, indicating that basketball players who respond more cautious to errors also tend to shoot more accurate immediately after the error, whereas adopting a more reckless attitude may negatively impact shooting accuracy. Interestingly, Neiman and Loewenstein<sup>14</sup> contended that, from a learning point of view, this cautious response of basketball players is detrimental to shooting accuracy. Specifically, they argue that players may overgeneralize as increasing the number of long-distance shots after made shots is associated with lower accuracy on these long-distance shots. However, considering this behavior through the lens of adaptive behavior offers a nuanced perspective. While increasing distance after made shots may indeed lead to lower accuracy on post-correct shots, reducing distance after missed shots conversely enhances accuracy on post-error shots. Thus, rather than being detrimental, players' cautious response can also be viewed as a strategy aimed at optimizing shooting accuracy immediately following errors.

Our exploratory analysis of expected points following made versus missed shots further informs this discussion. The calculations showed only a minimal difference of approximately 0.05 points in both the within-player and between-team contexts, with no observable difference in the within-team context. This suggests that, when considering the likelihood of attempting 2-point and 3-point shots after a missed vs. made shot along

with their respective success rates, increased shooting accuracy does not necessarily lead to a point difference immediately after the made vs. missed shot. Importantly, to ensure sufficient data points in each score category (0, 2 or 3 points) across all three social contexts, data from all players, teams and seasons were pooled for these calculations. As a result, the multilevel structure present in our primary analyses was lost, and we therefore focused on descriptive calculations rather than formal statistical tests. Furthermore, throughout our analysis of shooting distance and accuracy, we did not differentiate between 2-point and 3-point shots, which places these exploratory calculations at a different level than our primary analysis. Moreover, since overall game success operates at a higher level than shot-by-shot error adaptations, we cannot draw conclusions from these calculations about whether post-error caution improves overall game success across players, games and seasons. By inserting a total number of shots and error rate, both of which vary across seasons, games and players, we can only generate an overall estimate of expected number of total points. For example, if a total of 40 shots are taken in the within player context across all players in a game and these shots have a 49% miss rate (average error rate derived from Table 2), the total expected points would be 40.62 for these 40 shots. In contrast, if all shots followed the expected value for those after a made shot, the total expected points would be 39.6. While this difference of 1.02 points is small, it can be meaningful in the context of the NBA where every point can make the difference. These calculations illustrate that the practical relevance of the 0.05 expected point difference on a shot-by-shot basis also depends on the lens through which it is viewed (e.g., on a shot-by-shot, team, game or season level). Nonetheless, these remain expected point calculations which cannot just be equated to overall game success, as this also depends on defensive performance for example.

Our results also show that individual differences between players contributed more to the observed variability compared to differences between teams or games. Combined with the observed positive correlation between post-error cautiousness and accuracy, this result suggests that it could be valuable for coaches and sports psychologists to investigate athletes' individual post-error tendencies. Furthermore, this correlation suggests a promising avenue for future research to explore strategies aimed at influencing athletes' post-error behavior. While our study revealed a positive correlation over time in players' post-error cautiousness scores, these effects fall within the small to medium range according to Cohen's guidelines<sup>27</sup>. Notably, Neiman and Loewenstein<sup>14</sup> reported a higher autocorrelation of 0.43 in players' adaptations to their own errors, which might partially be explained by the different behavioral measures of shooting strategy. Despite this discrepancy, both results imply the potential for changing players' post-error behavior. These insights could prove particularly valuable for coaches and sports psychologists seeking to optimize athletes' responses to errors. Since the exact mechanisms driving players' error adaptations remain unclear based on game data, future research could explore whether these adaptations are purely driven by the negative affect errors trigger, or if other factors, such as athlete confidence, perfectionism or collective collapse also play a role<sup>3,13,22</sup>. By gaining a deeper understanding of the individual differences, the potential for change, and the mechanisms underlying players' post-error adaptations, coaches and sports psychologists could tailor interventions to improve players' ability to adaptively respond to mistakes.

While our study represents one of the first analyses of social post-error adaptations in sports, a notable limitation pertains to the exclusive focus on male basketball. This choice was primarily driven by the availability of data and the well-defined shot and team structure in basketball. Additionally, while these results hold for professional players, it remains uncertain whether similar patterns would be observed for non-professional or amateur players. As the pressure to perform is especially high in professional sports<sup>3</sup>, one could expect that error monitoring is particularly heightened among NBA professionals. Broadening the scope of these analyses to other sports and include female athletes as well as non-professional athletes, holds the potential to give additional insights into the universality of these effects across different sports and levels. Such an extension and diversity could also provide further insights into whether the observed effects are indeed driven by athletes' internal control processes.

In line with previous 'hot/cold hand' research, we operationalized successful and erroneous shots based on the objective outcome of each attempt, without making assumptions about players' perceptions of these shots. However, in some situations, players might not consider missed shots from long distances as erroneous due to the low expectation of success from such distances. Taking shot expectation into account when defining successful and erroneous shots could therefore offer a more nuanced classification of errors in future research. Additionally, in time-sensitive situations or under high defensive pressure, players might consider long-distance shots as a favorable strategy to try and score within the limited time available. While we did not consider any contextual factors such as game clock, shot clock, defensive pressure or current game score, these factors could potentially influence players' decision-making. For example, previous research has indeed shown that time constraints and pressure impact the quality of athletes' decisions<sup>10,11</sup>. So, it is plausible that under high-pressure situations, such as when a team is trailing by only a few points and little time is left, players switch to a different strategy and exhibit post-error recklessness. Additionally, player-related variables, such as fatigue<sup>28,29,30</sup>, might also impact shooting distance. Therefore, future data analysis studies or field experiments should explore the impact of additional factors such as shot expectation, game clock, shot clock, game score, defensive pressure or player fatigue. This would contribute to a more nuanced understanding of social error monitoring in basketball and related sports.

In conclusion, our study contributes to the understanding of social error monitoring in a real-world social setting by revealing that professional basketball players adopt a more cautious approach after errors compared to successful shots. Importantly, this behavioral adaptation seems to be sensitive to the social game context, specifically whether the error is by the player himself, a teammate or an opponent. While the precise mechanisms driving these effects remain to be elucidated, our results suggest that the adaptations to own and teammates' errors are at least partially driven by internal control processes of the shooting player. In contrast, our analysis suggests that the adaptations in response to opponents' errors may arise from different monitoring processes.

Building on decades of research on error monitoring, our study extends findings from controlled lab setting to a complex real-world social context, potentially enhancing the broader applicability of cognitive theories and models on social error monitoring. Further, by shedding light on basketball players' post-error responses our study offers a crucial initial step towards the development of training or interventions aimed at refining their responses to errors, thereby potentially enhancing performance.

### Data availability

The data analyzed in this study comes from a third-party source (<http://www.basketballgeek.com/data/>), and was accessed for download on 18th October, 2023. This dataset includes open-source data from four NBA seasons, and was fully anonymized before analysis. Since this study involved the analysis of online available, open-source data, no ethical approval was required. All anonymized and processed datafiles are accessible via OSF (<https://osf.io/vcj3b/>).

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### References

- Wessel, J. R. An adaptive orienting theory of error processing. *Psychophysiology* **55**, e13041. <https://doi.org/10.1111/psyp.13041> (2018).
- Danielmeier, C., Ullsperger, M. & Post-Error, A. *Front. Psychol.* **2** <https://doi.org/10.3389/fpsyg.2011.00233> (2011).
- Flett, G. L. & Hewitt, P. L. The perils of perfectionism in sports and exercise. *Curr. Dir. Psychol. Sci.* **14**, 14–18. <https://doi.org/10.1111/j.0963-7214.2005.00326.x> (2005).
- Dutilh, G. et al. Testing theories of post-error slowing. *Atten. Percept. Psychophys.* **74**, 454–465. <https://doi.org/10.3758/s13414-011-0243-2> (2012).
- Williams, P., Heathcote, A., Nesbitt, K. & Eidels, A. Post-error recklessness and the hot hand. *Judgm. Decis. Mak.* **11**, 174–184. <https://doi.org/10.1017/S1930297500007282> (2016).
- Schuch, S. & Tipper, S. P. On observing another person's actions: influences of observed inhibition and errors. *Percept. Psychophys.* **69**, 828–837. <https://doi.org/10.3758/bf03193782> (2007).
- de Bruijn, E. R., Mars, R. B., Bekkering, H. & Coles, M. G. Your mistake is my mistake. Or is it? Behavioural adjustments following own and observed actions in cooperative and competitive contexts. *Q. J. Exp. Psychol.* **65**, 317–325. <https://doi.org/10.1080/10.1080/17470218.2010.545133> (2012).
- Núñez Castellar, E., Notebaert, W., Van den Bossche, L. & Fias, W. How monitoring other's actions influences one's own performance. *Exp. Psychol.* **58**, 499–508. <https://doi.org/10.1027/1618-3169/a000118> (2011).
- Paap, K. R., Anders-Jefferson, R., Zimiga, B., Mason, L. & Mikulinsky, R. Interference scores have inadequate concurrent and convergent validity: should we stop using the flanker, Simon, and Spatial Stroop tasks? *Cogn. Research: Principles Implications*. **5**, 7. <https://doi.org/10.1186/s41235-020-0207-y> (2020).
- Raab, M. & Laborde, S. When to Blink and when to think: preference for intuitive decisions results in faster and better tactical choices. *Res. Q. Exerc. Sport.* **82**, 89–98. <https://doi.org/10.1080/02701367.2011.10599725> (2011).
- Ashford, M., Abraham, A. & Poolton, J. Understanding a Player's Decision-Making Process in Team Sports: A Systematic Review of Empirical Evidence. *Sports (Basel Switzerland)*. **9** <https://doi.org/10.3390/sports9050065> (2021).
- Avugos, S., Köppen, J., Czienskowski, U., Raab, M. & Bar-Eli, M. The hot hand reconsidered: A meta-analytic approach. *Psychol. Sport Exerc.* **14**, 21–27. <https://doi.org/10.1016/j.psychsport.2012.07.005> (2013).
- Gilovich, T., Vallone, R. & Tversky, A. The hot hand in basketball: on the misperception of random sequences. *Cogn. Psychol.* **17**, 295–314. [https://doi.org/10.1016/0010-0285\(85\)90010-6](https://doi.org/10.1016/0010-0285(85)90010-6) (1985).
- Neiman, T. & Loewenstein, Y. Reinforcement learning in professional basketball players. *Nat. Commun.* **2**, 569. <https://doi.org/10.1038/ncomms1580> (2011).
- Csapo, P., Avugos, S., Raab, M. & Bar-Eli, M. The effect of perceived streakiness on the shot-taking behaviour of basketball players. *Eur. J. Sport Sci.* **15**, 647–654. <https://doi.org/10.1080/17461391.2014.982205> (2015).
- Attali, Y. Perceived hotness affects behavior of basketball players and coaches. *Psychol. Sci.* **24**, 1151–1156. <https://doi.org/10.1177/0956797612468452> (2013).
- Van der Borgh, L., Desmet, C. & Notebaert, W. Strategy changes after errors improve performance. *Front. Psychol.* **6** <https://doi.org/10.3389/fpsyg.2015.02051> (2016).
- Viechtbauer, W. Conducting Meta-Analyses in R with the metafor package. *J. Stat. Softw.* **36**, 1–48. <https://doi.org/10.18637/jss.v036.i03> (2010).
- Worthy, D. A., Hawthorne, M. J. & Otto, A. R. Heterogeneity of strategy use in the Iowa gambling task: A comparison of win-stay/lose-shift and reinforcement learning models. *Psychon. Bull. Rev.* **20**, 364–371. <https://doi.org/10.3758/s13423-012-0324-9> (2013).
- Tamura, K. & Masuda, N. Win-stay lose-shift strategy in formation changes in football. *EPL Data Sci.* **4**, 9. <https://doi.org/10.1140/epjds/s13688-015-0045-1> (2015).
- Csapo, P. & Raab, M. Hand down, man down. Analysis of defensive adjustments in response to the hot hand in basketball using novel defense metrics. *PLoS One*. **9**, e114184. <https://doi.org/10.1371/journal.pone.0114184> (2014).
- Apitzsch, E. Coaches' and elite team players' perception and experiencing of collective collapse. *Athletic Insight*, **1**, 57–74 (2009).
- Musco, M. A., Zazzera, E., Paulesu, E. & Sachelì, L. M. Error observation as a window on performance monitoring in social contexts? A systematic review. *Neurosci. Biobehavioral Reviews*. **147**, 105077. <https://doi.org/10.1016/j.neubiorev.2023.105077> (2023).
- Dignath, D., Eder, A. B., Steinhauser, M. & Kiesel, A. Conflict monitoring and the affective-signaling hypothesis—An integrative review. *Psychon. Bull. Rev.* **27**, 193–216. <https://doi.org/10.3758/s13423-019-01668-9> (2020).
- Aarts, K., De Houwer, J. & Pourtois, G. Erroneous and correct actions have a different affective valence: evidence from erps. *Emotion* **13**, 960–973. <https://doi.org/10.1037/a0032808> (2013).
- Kahneman, D. & Tversky, A. In *Handbook of the Fundamentals of Financial Decision Making: Part 199–127* (World Scientific, 2013).
- Cohen, J. D. *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). (1988).
- Skala, F. & Zemková, E. Effects of acute fatigue on cognitive performance in team sport players: does it change the way they perform? A scoping review. *Appl. Sci.* **12**, 1736 (2022).
- Almonroeder, T. G., Tighe, S. M., Miller, T. M. & Lanning, C. R. The influence of fatigue on decision-making in athletes: a systematic review. *Sports Biomech.* **19**, 76–89. <https://doi.org/10.1080/14763141.2018.1472798> (2020).
- Chang, Y. K., Labban, J. D., Gapin, J. I. & Etnier, J. L. *Brain Res.* **1453** 87–101 (2012).

### Author contributions

A.D.: Conceptualization, Methodology, Formal Analysis, Data Curation, Visualization, Writing – Original Draft, Writing – Review & Editing, Funding acquisition. G.P.: Methodology, Writing - Review & Editing, Supervision. T.L.: Methodology, Writing – Review & Editing. W.N.: Conceptualization, Methodology, Writing – Review & Editing, Supervision.

### Declarations

#### Competing interests

The authors declare no competing interests.

#### Additional information

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**Correspondence** and requests for materials should be addressed to A.D.

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