

The role of visual feedback in metacognitive judgments of motor performance

Lise Brun^{a,1}, Perrine Porte^{a,*,1}, Marianne Cottin^{a,2}, Éric Guinet^a, Aïna Chalabaev^b, Estelle Palluel^c, Nathan Faivre^a, Céline Souchay^a

^a Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, LPNC, 38000 Grenoble, France

^b Univ. Grenoble Alpes, SENS, 38000 Grenoble, France

^c Univ. Grenoble Alpes, CNRS UMR 5525, VetAgro Sup, Grenoble INP, TIMC, 38000 Grenoble, France

ARTICLE INFO

Keywords:

Motor metacognition
Confidence judgments
Metacognitive architecture
Global judgments
Visual feedback

ABSTRACT

Predicting the outcome of one's actions is crucial for effective behaviour, yet the mechanical underpinnings of this metacognitive ability remain poorly understood. We investigated the impact of visual feedback on basketball players' ability to monitor the accuracy of their free throws. In two preregistered experiments ($N = 39$ & $N = 21$), basketball players performed a free-throw basketball task while a visual occlusion was triggered either immediately after the ball left their hands or after 200, 400, 600, or 800 ms. Participants then predicted whether the ball was in the hoop and reported their confidence in their answer. In both experiments, we found that the amount of visual feedback co-varied positively with the capacity to adjust confidence to predictions following successful, but not failed, throws. This shows that during sport self-evaluation, people rely on outcome-related visual cues primarily when assessing success, whereas failure may be judged based on internal signals. Moreover, to investigate metacognitive architecture, we compared local and global, and prospective and retrospective, judgments, observing that the metacognitive bias differed as a function of the judgments. This suggests that different cues are used for the different metacognitive judgments.

1. Introduction

In the course of a day, we engage in numerous cognitive and motor activities, and being able to assess our own performance is crucial for making decisions that align with our capabilities. This capacity, known as metacognition, refers to the ability to monitor and control our cognitive processes (Flavell, 1979).

An influential view of metacognition (Nelson & Narens, 1990) defines the meta-level as involving second-order representations and behaviours, and the object-level (or task-level) as involving first-order representations and behaviours. At the meta-level, the metacognitive architecture can be represented by two interrelated levels: The information-based level, which encompasses knowledge and beliefs about one's own cognitive capabilities (such as 'I am better at basketball than tennis'), and the experience-based level, which is directly related to the task at hand (Koriat, 2000). Different measures have been proposed to investigate these two levels (Mazancieux et al., 2023). Direct

measures are defined by asking participants to self-reflect about a first-order task (such as throwing a ball) and report on their self-reflection. These so-called metacognitive judgments, therefore, involve subjective assessments about one's performance. One main distinction is between prospective and retrospective judgments, where prospective judgments are made before the task and retrospective judgments after the task. Retrospective judgments are more accurate than prospective judgments, due to the availability of the information present at the moment of the task (e.g., Fleming et al., 2016; Kelemen et al., 2000; Siedlecka et al., 2016). Another main distinction is between local and global judgments: local judgments are made on each trial of a task, whereas global judgments are made across the entire task. Retrospective local confidence judgments are the most common type of metacognitive judgments used (Rahnev et al., 2020). Nonetheless, despite being less often used, global judgments provide valuable insight into another facet of metacognition, often linked to self-efficacy (Mazancieux et al., 2023). Several studies found differences between local and global judgments in

* Corresponding author at: Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, LPNC, 38000 Grenoble, France.

E-mail address: perrine.porte@univ-grenoble-alpes.fr (P. Porte).

¹ Shared contribution.

² Present address: Centre de Recherche en Neurosciences de Lyon (CRNL), INSERM U1028 – CNRS UMR5292, Université de Lyon, Lyon, France.

memory or perceptual tasks (e.g., Frank & Kuhlmann, 2017; Hoven et al., 2022; Rouault & Fleming, 2020; Souchay et al., 2006). Seow et al. (2021) therefore proposed a hierarchy of metacognitive judgments where local judgments shape global self-beliefs, which, in turn, are likely to influence local assessments. The field of metacognition has therefore seen major developments in how to best measure metacognitive behaviour. However, because motor metacognition is a relatively new area of research, little is known about how these results extend to motor actions. The present work, therefore, sought to explore how different types of metacognitive judgments relate to one another in a motor context, thereby providing evidence on whether metacognitive architecture is shared across domains.

To predict the outcome of one's actions, multiple sensory cues can be used. Research on action anticipation in athletes often uses occlusion paradigms to manipulate the availability of information (for a review, see Williams & Jackson, 2019). They found that, in basketball, visual information is important: the longer participants can see the ball's trajectory, the better they can anticipate whether it will be successful (Aglioti et al., 2008). However, such studies typically adopt a third-person perspective, where participants watch another player perform an action, and therefore do not reveal which cues are used to judge their own actions.

To examine action anticipation abilities from a first-person perspective, several researchers (Cañal-Bruland et al., 2015; Maglott et al., 2019; Maglott & Shull, 2019) used a paradigm in which basketball players performed a free-throw task without visual feedback and had to anticipate the result of their throws: As the ball left the participant's hand, a visual occlusion was triggered manually via liquid crystal glasses. Participants then simply predicted if the ball was in or out of the hoop. The results showed that college basketball players anticipated the outcome of their successful shots adequately without visual information, but not for their failed shots. This pattern of results can be explained by participants' response bias, as they tended to overestimate that their throws were successful (Maglott et al., 2019). In another study, Cañal-Bruland et al. (2015) also investigated the role of proprioceptive information by including two basketball players: one performing the throws while the other observed them. The vision of both players was manually occluded at the same time, and each independently predicted the outcome of the throw. No significant difference was observed between the observer and the performer on this action anticipation task, suggesting that proprioceptive information does not seem to improve monitoring skills, a conclusion supported by other data (Franklin et al., 1978; Jagacinski et al., 1977; Rieser et al., 2014). However, these studies focused on visual information in binary terms (present vs absent), and examined only action anticipation performance, which corresponds to a first-order level of representation. As a result, it leaves open the question of how varying amounts of visual information shape not only the first-order level of representation, but also the second-order level and, notably, local metacognitive judgments such as local retrospective confidence judgments.

The objective of the present study was to characterize more deeply motor metacognitive mixing first-order and second-order measures in an ecological task. Thus, in two experiments, basketball players performed a free-throw basketball task during which a visual occlusion was automatically triggered at different delays after the ball left their hands. After each throw, participants predicted whether their throw was successful and how confident they were in that prediction. Building on results from third-person action anticipation literature (e.g., Aglioti et al., 2008), Experiment 1 tested our main preregistered hypothesis that the more visual information basketball players had access to, the more appropriately they would adapt their confidence to the accuracy of their prediction. Based on findings from Maglott et al. (2019), this effect was expected to be moderated by the outcome of the throw and was replicated in Experiment 2 with a more skilled group of players. The second objective of these experiments was to compare participants' abilities to estimate their performance locally and globally in order to

explore and compare the different facets of motor metacognition, and thus test whether the current view of the metacognitive architecture holds in the motor domain.

2. Method

2.1. Transparency and openness

The hypotheses, methods, and main analysis plan were preregistered, and all study materials, data, and analysis scripts are publicly available on the Open Science Framework platform (<https://osf.io/74s8v/overview>; <https://osf.io/f693p/overview>).

2.2. Participants

All participants spoke French and self-reported being of legal age, having normal or corrected-to-normal vision, and not having a movement disorder. They all signed a free and informed consent before the beginning of the experiment. These experiments respect the Declaration of Helsinki and were approved by the local ethics committee in Grenoble (France).

2.2.1. Experiment 1

Forty-one basketball players participated in Experiment 1. In accordance with our pre-registration criteria, two participants were excluded from the analyses because they succeeded in fewer than 10 successful throws out of 100. The statistical analyses were conducted on 39 recreational basketball players (30 men and 9 women, mean age = 21.69 ($SD = 3.95$)). They played basketball at least once a week (average hours per week: 4.23 h ($SD = 3.12$)), and had been playing basketball from, on average, 8.67 ($SD = 5.23$) years. Participants were paid 10€ for their participation.

2.2.2. Experiment 2

Our pre-registration plan was an open-ended sequential Bayes analysis. We planned to stop data acquisition when a pre-defined statistical model reached substantial evidence for either H_0 ($BF < 1/3$) or H_1 ($BF > 3$) for our effect of interest: the three-way interaction between the confidence, delay, and outcome of throw on the accuracy of prediction. The stopping rule criterion was already met when performing the first Bayes Factor sequential analysis with 21 participants.

One objective of Experiment 2 was to replicate Experiment 1 with a more homogeneous and expert group of players. The 21 participants (15 men and 6 women, mean age = 19.57 ($SD = 1.64$)) were thus basketball players of the basketball specialty in sports studies. They played basketball at least once a week (average hours per week: 5.56 h ($SD = 2.33$)), and had been playing for, on average, 6.3 ($SD = 2.73$) years. They were paid 20€ for their participation. We increased compensation by 10€ compared with the first experiment to motivate basketball players to take part in the study. No participants were excluded.

2.3. Apparatus

The experiment took place outside under standard free-throw shooting conditions: 4.57 m from a 3.05 m high basket. Participants wore a thin glove on which all finger locations except for the index finger were cut out to preserve maximum tactile information during throws. On the index finger, a pressure sensor (Round Force Sensor

FSR402, Grove) was glued and wired to an electronic board (Arduino Uno WiFi V2 board ABX00021-R, Go Tronic), which was connected by cable to Plato liquid crystal glasses (PLATO by Translucent Technologies, Toronto, Canada). When the sensor detected a decrease in force to a threshold (0.0976 V), it triggered a visual occlusion after a variable delay. The whole equipment was remotely controlled by Bluetooth with MATLAB (R2020B). Participants also wore earphones that played white noise and noise-cancelling headphones to prevent auditory feedback.³

2.4. Procedure

Participants performed a free-throw basketball task during which a visual occlusion was automatically triggered at different delays after the ball left their hands. The visual occlusion could occur 0, 200, 400, 600, or 800 ms after the ball was released. Within each block of 10 throws, the order of the visual occlusion delays was randomized (ensuring that each visual occlusion delay was repeated twice per block). Participants had no auditory feedback. After releasing the ball, participants estimated orally whether the ball was inside or outside the hoop and then indicated how confident they were in their response using a four-point scale: “1 - Not sure,” “2 - Moderately sure,” “3 - Sure,” and “4 - Very sure”. Once the confidence judgment had been made, the visual occlusion was removed, and the participant could prepare for the next throw.

Participants started with two practice sessions. In the first one, they shot 10 free throws without visual occlusion to familiarize themselves with the environment and the equipment. In the second one, they performed an experimental block (i.e., 10 free throws), with auditory feedback, to familiarize themselves with the experimental procedure.

Once the training was over, participants performed the test phase, which comprised 10 experimental blocks (i.e., 100 trials, 20 per condition). Participants could take breaks between each block if they wished. They received no feedback regarding their performance or their metacognitive performance. At the end of the test phase, they made a retrospective global judgment (i.e., “You just made 100 throws, how many do you think you succeeded?”). In total, the experiment lasted approximately 1 h and 15 min. Fig. 1 illustrates the experimental procedure.

Experiment 2 was a conceptual replication of Experiment 1: the procedure was identical except for three changes. First, we modified the instructions by informing participants that for each successful throw, they would earn an additional 12 cents. This enabled us to check that the participants were not deliberately failing their shots so that they could be sure of evaluating them as such (i.e., knowingly reducing their sporting performance to improve their metacognitive performance). Second, we added two additional trials per block (resulting in 12 trials per block, 120 trials in total) in which participants shot without visual occlusion to assess whether participants understood the instructions, as they should not fail to predict the outcome of the throw if they saw the outcome; these trials were excluded from the main analysis. Finally, we added a prospective global judgment before the beginning of the test session (i.e., “You are going to perform 120 free throws, how many do you think you will make?”).

2.5. Statistical analysis

All analyses were performed in R. Frequentist analyses were pre-registered for Experiment 1, while Bayesian analyses were pre-registered for Experiment 2: for the sake of consistency, we have

³ The participants also wore an inertial measurement unit (Xsens DOT Movella, Enschede, Netherlands) on their dominant hand in Experiment 1 (and two additional ones in Experiment 2: one on the forearm and one on the arm). Defects in the time synchronisation of the control units with the rest of the experiment and several data acquisition problems made statistical analyses difficult, which is why they are not presented in this manuscript.

chosen to report only the results of the Bayesian analyses in the main text (see Appendix A for results of the frequentist analyses of Experiment 1). In Experiment 1, the models were fitted with uninformed priors for fixed effects (normal(0,2)). In Experiment 2, the models were both fitted with uninformed priors (normal(0,2)) and informed priors based on the posterior means and 1.5 times SDs of fixed effects found in Experiment 1 (Chancel et al., 2025; Zampieri et al., 2021). We report results from uninformed analysis, as the results were similar or more conservative. As preregistered, we considered an effect to be conclusive if the $BF_{10} > 3$ and the posterior probability distribution had a 95% credible interval that did not overlap with zero. Bayes Factors were computed through the Savage-Dickey method.

To compute the prediction accuracy, we combined the objective performance and participants' predictions. The prediction is considered correct if it matches the outcome of the throw (0 for an inaccurate prediction, 1 for an accurate prediction).

In Experiment 1, data from 5 trials out of 4100 are missing due to data acquisition issues. In Experiment 2, there were no missing data (see Appendix B for sanity check results).

2.5.1. Main analysis

To evaluate how accurately participants' confidence tracked their accuracy, metacognitive performance was quantified through the slope of mixed-effects logistic regression on prediction accuracy, with confidence, occlusion delay, and throw outcome as fixed effects (all centered). Random effects included random intercepts and random slopes for each fixed effect by participant.

2.5.2. Analysis to compare global and local judgments

To make global and local judgments comparable, we first made the sum of the local judgments (i.e., the number of times participants answered “in”). We computed the absolute differences between the judgment estimate and the actual performance to investigate the difference in prediction error, and the signed differences to investigate differences in terms of bias. As the magnitude of these differences may be influenced by actual performance on the task, we divided prediction error by the actual performance of each participant so that prediction errors could be compared across participants independently of their overall performance level. For example, participant A, predicting 15 and succeeding on 25 throws, and participant B, predicting 65 and succeeding on 75 throws, would both obtain a prediction error of 10 without performance normalization whereas they would obtain relative errors of 40% and 13%, respectively, with the normalization.

2.5.2.1. Experiment 1. We investigated whether global and local judgments differed in terms of prediction error and bias. We ran Bayesian one-sample *t*-tests to compare global and local bias to 0. To do so, we used the package *BayesFactor* (Morey & Rouder, 2012) and the function *ttestBF* with the default priors. A positive bias score (signed difference) indicates overestimation, while a negative bias score indicates underestimation. We also ran Bayesian linear regressions on bias and prediction error with uninformed priors (normal(0,2)) as a function of the type of judgments (i.e., local vs global).

2.5.2.2. Experiment 2. In Experiment 2, we added a global prospective judgment. Participants performed 120 throws and rated their overall performance out of 120. Because the 20 non-occluded trials were excluded from the local-judgment analysis, these global estimates were normalized to 100. As in Experiment 1, we ran Bayesian one-sample *t*-tests to compare whether the bias of each judgment differed from 0. We also ran Bayesian linear regressions on bias and prediction error with uninformed priors (normal(0, 2)) as a function of the type of judgments. As preregistered, we tested two orthogonal contrasts: the first comparing local judgments and global judgments (mean of prospective and retrospective), and the second comparing prospective and retrospective

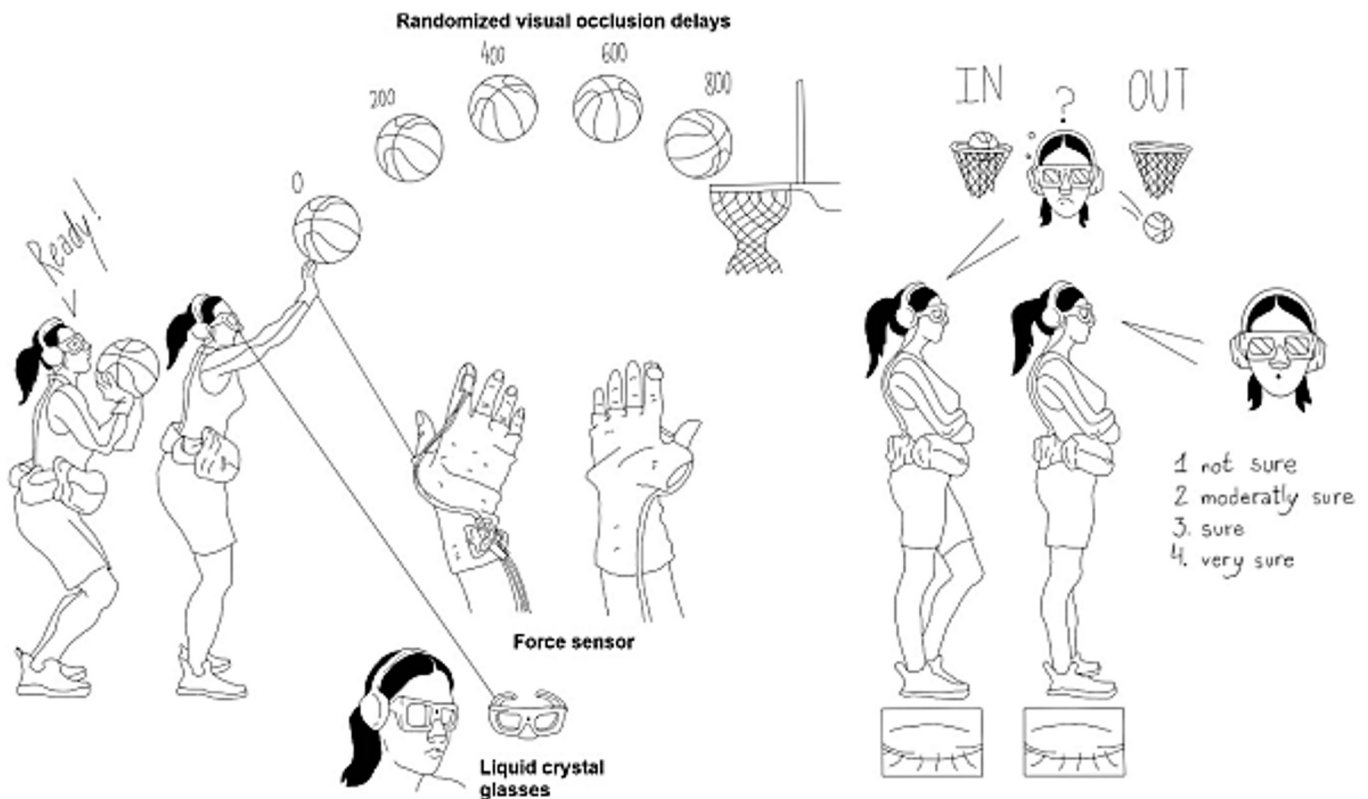


Fig. 1. Experimental procedure. On each trial, participants signalled that they were ready and threw the ball toward the hoop. The release of the ball was detected by a force sensor placed on the participant's index finger, and this information was sent to liquid crystal glasses, which triggered a visual occlusion. The visual occlusion could occur immediately, 200, 400, 600, or 800 ms after the ball release. Participants then indicated whether they thought the ball was in or out of the hoop and indicated their degree of confidence in their response on a four-point scale.

global judgments.

3. Results

In Experiment 1, 38.58% ($SD = 16.05$) of throws were successful. Performance was better in Experiment 2, with an average 57.59% ($SD = 15.31$) successful throws.

3.1. Accuracy of predictions

In Experiment 1, participants accurately predicted 54.67% ($SD = 11.12$) of their free throws, and 58.44% ($SD = 10.7$) in Experiment 2. In both experiments, participants tended to predict that their throw was successful, as indicated by a negative response criterion (**Exp.1:** $M = -0.22$, 95% HDI $[-0.33, -0.12]$, $BF1 = 410.99$; **Exp.2:** $M = -0.16$, 95% HDI $[-0.29, -0.04]$, $BF1 = 4.43$).

The Bayesian logistic regression analysis on the accuracy of predictions (see Fig. 2) revealed a main effect of delay in Experiment 1 ($\hat{\beta} = 0.12$ [0.06, 0.18], $BF1 = 167.65$), but evidence was inconclusive in Experiment 2 ($\hat{\beta} = 0.13$ [0.03, 0.22], $BF1 = 0.53$). Furthermore, a main effect of outcome revealed that participants' predictions were more accurate for successful trials than for failed trials (**Exp.1:** $\hat{\beta} = 0.9$ [0.48, 1.33], $BF1 > 1000$; **Exp.2:** $\hat{\beta} = 0.79$ [0.29, 1.29], $BF1 = 14.04$). While evidence for the interaction between occlusion delay and throw outcome in Experiment 1 was inconclusive ($\hat{\beta} = 0.25$ [0.09, 0.41], $BF1 = 2.85$), evidence in Experiment 2 suggested that the effect of delay on prediction's accuracy didn't differ between successful and failed throws ($\hat{\beta} = 0.19$ $[-0.09, 0.48]$, $BFO = 5.47$).

3.2. Adaptation of confidence ratings to the accuracy of predictions

We next examined how well confidence judgments tracked the accuracy of predictions (see Fig. 2). The analysis revealed extreme evidence for an effect of the confidence on prediction accuracy (**Exp.1:** $\hat{\beta} = 0.42$ [0.33, 0.51], $BF1 > 1000$; **Exp.2:** $\hat{\beta} = 0.51$ [0.35, 0.7], $BF1 > 1000$), meaning that participants were more confident in their correct than incorrect predictions, irrespective of the outcome of the throw. In Experiment 1, this confidence effect varied with the outcome of the throw ($\hat{\beta} = -0.61$ $[-1, -0.22]$, $BF1 = 10.29$): basketball players adapted their confidence more adequately in failed throws than in successful ones, but evidence was inconclusive in Experiment 2 ($\hat{\beta} = -0.46$ $[-1.16, 0.23]$, $BF1 = 0.43$).

Additionally, and in accordance with our hypothesis, we found that, in Experiment 1, confidence tracked accuracy better as visual feedback increased ($\hat{\beta} = 0.11$ [0.05, 0.17], $BF1 = 4.78$). But, again, evidence was inconclusive in Experiment 2 ($\hat{\beta} = 0.16$ [0.04, 0.29], $BF1 = 0.90$).

However, and importantly, in both experiments, the analysis revealed moderate evidence (**Exp.1**) and extreme evidence (**Exp.2**) for an interaction between confidence, delay and outcome of the throw (**Exp.1:** $\hat{\beta} = 0.23$ [0.09, 0.36], $BF1 = 8.84$; **Exp.2:** $\hat{\beta} = 0.6$ [0.39, 0.81], $BF1 > 1000$). In other words, the delay of occlusion had a bigger effect on confidence in successful throws than in failed throws. We performed a post-hoc analysis to explore the interaction effect of confidence and delay on accuracy in failed throws only. The results indicated moderate evidence for the null hypothesis (**Exp.1:** $\hat{\beta} = 0.01$ $[-0.06, 0.08]$, $BFO = 55.00$; **Exp.2:** $\hat{\beta} = -0.12$ $[-0.27, 0.02]$, $BFO = 7.04$): confidence did not track accuracy better as visual feedback increased in failed throws.

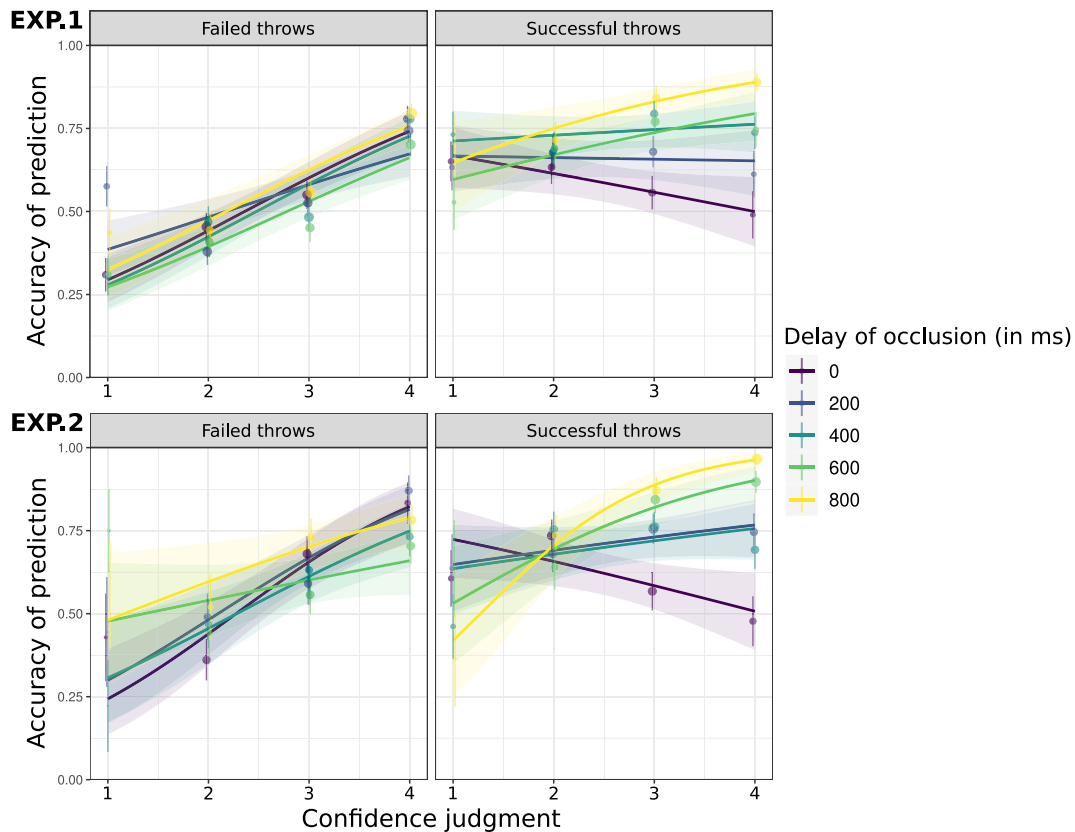


Fig. 2. Main behavioral results. Results from the mixed-effects logistic regression on the accuracy of the prediction as a function of the confidence, delay of occlusion, and outcome of the throw. Dots represent the mean of the observed accuracy of the predictions, and error bars represent the observed standard errors. The solid lines represent the logistic regression fit, and the shaded areas correspond to the model's posterior predicted 95% confidence intervals. Upper panels show results from Experiment 1 and lower panels from Experiment 2.

3.3. Comparing local and global judgments

3.3.1. Experiment 1

The Bayesian paired *t*-test comparing local and global judgment prediction error was inconclusive ($\hat{\beta} = 0.31$ [0.07, 0.54], $BF1 = 1.51$).

We next looked at the signed difference instead of the absolute difference. We first found that the mean bias of local judgments was positive and different from 0 ($BF1 = 223.17$), whereas no conclusion could be made about the mean of the global judgments' bias ($BF1 = 0.17$). However, we found extreme evidence for a difference between local and global judgments on bias ($\hat{\beta} = 0.78$ [0.6, 0.98], $BF1 > 1000$): participants overestimated their performance in local judgments more than in global judgments (see Fig. 3).

3.3.2. Experiment 2

In Experiment 2, we added a global prospective judgment. The Bayesian linear regression revealed that local and global judgment didn't differ in terms of prediction error ($\hat{\beta} = 0.02$ [-0.01, 0.05], $BF0 = 33.63$). However, at the global level, participants were more precise in their prospective than in their retrospective judgments ($\hat{\beta} = 0.05$ [0.02, 0.08], $BF1 > 1000$).

We next looked at the bias. We found that the mean of both global and local judgments bias differed from 0 ($BF1 > 1000$ for the three analyses). The Bayesian linear regression revealed a difference between local and global judgments ($\hat{\beta} = -0.09$ [-0.11, -0.07], $BF1 > 1000$), indicating that participants overestimated their performance in local rather than in global judgments. At the global level, we also observed a difference between retrospective and prospective judgments ($\hat{\beta} = -0.06$ [-0.07, -0.04], $BF1 > 1000$) indicating that participants

underestimated their performance in prospective judgments (see Fig. 3).

4. Discussion

The present research aims to assess the role of visual information on participants' metacognitive abilities in an ecological free-throw basketball task and to provide insights into the architecture of metacognition. To achieve this, we manipulated the amount of visual information available to participants before they assessed their performance and confidence. To our knowledge, this is the first study to investigate motor metacognition through retrospective local confidence and global judgments in an ecological sports task.

First, we replicated previous findings (Cañal-Bruland et al., 2015; Maglott et al., 2019) showing that participants tended to overestimate the positive outcome of their throws.

In accordance with our preregistered hypothesis, we found an effect of the amount of visual information on metacognition: the more visual evidence participants had, the more accurately they aligned their confidence judgments to the accuracy of their predictions. Importantly, this effect was moderated by the outcome of the throw, that is, present only for successful throws, and absent for failed ones. This suggests that players did not use information in the same way to monitor their successful versus failed throws.

A possible explanation for this asymmetry is that a successful throw requires accuracy across all stages of motor control (planning, execution, and the processing of the sensory consequences of the action). In contrast, a throw can be inferred as failed based on information arising at any of these stages. Failure in planning can be detected through discrepancies between predicted and intended sensory consequences, as described in hybrid models of movement (Desmurget & Grafton, 2000;

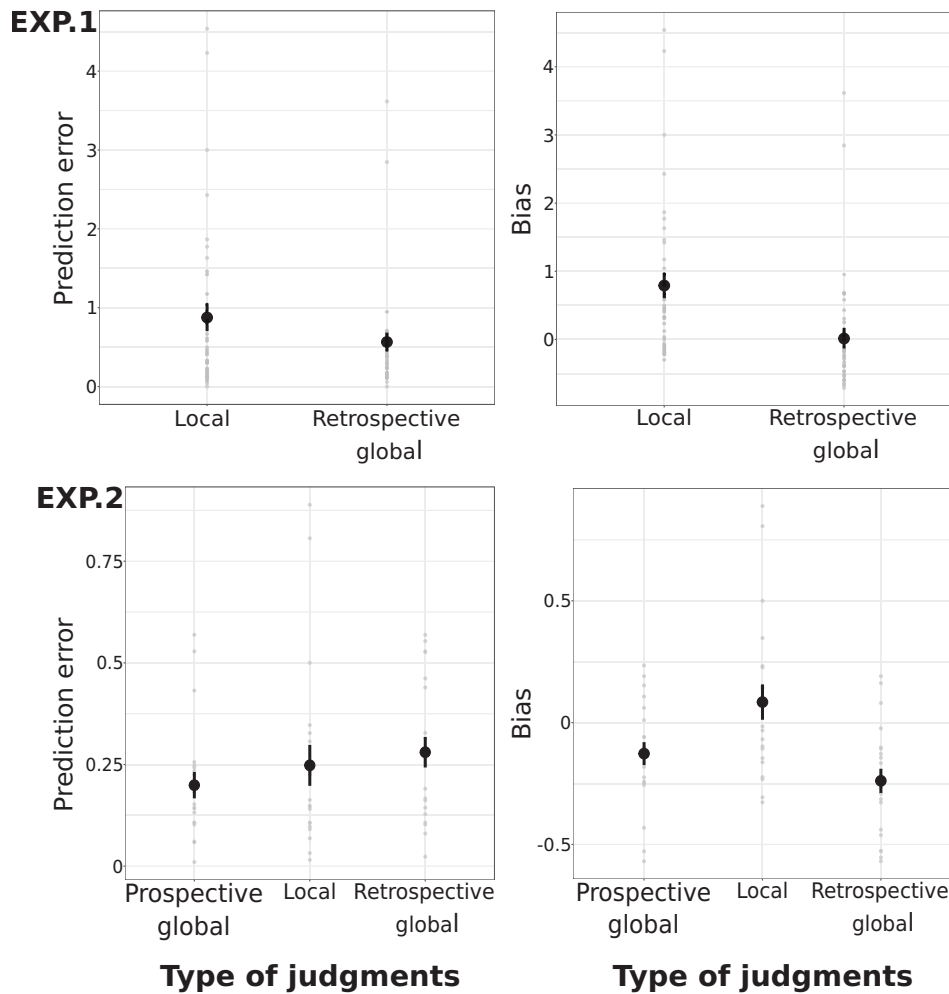


Fig. 3. Effect of the type of judgments. Left panels represent the prediction error (absolute difference between the judgment and the actual performance). Right panels represent the bias (signed difference between the judgment and the actual performance). Dots with error bars represent the observed mean with its standard errors. Each small grey dot represents a participant.

Joch et al., 2017). Failure during movement execution can be inferred from online sensory feedback – particularly proprioceptive (Kumawat et al., 2022; Rieser et al., 2014); consistent with this, Culot et al. (2025) found that the availability of visual information did not improve metacognitive evaluation of motor errors. Finally, failure can be inferred through the processing of the sensory consequences of the action (Maurer et al., 2015). Because failure, but not success, can be inferred before the sensory consequences become available, visual feedback on these consequences plays a smaller role in evaluating failed compared to successful throws. Visual information might play a bigger role in nearly missed trials; unfortunately, a limitation of our study is that we did not collect quantitative data describing failed throws (i.e., the degree to which each throw deviated from success). Further research is needed to investigate how visual information may be used as a function of the magnitude of the failure. To gain deeper insights into our results, it would be valuable to compare different versions of our task by varying the amount of visual, proprioceptive, and motor evidence. For example, participants could be filmed during the task and then rewatch their movements, creating a visual-only condition (without proprioceptive input or motor command).

The dissociation between successful and failed throws could be important in the context of sports competitions: being able to predict whether one is going to score or not can determine the future positioning of players (MacIntyre et al., 2014; Maglott et al., 2019). Hence, the sooner players can determine whether their throw is a success or a

failure, the sooner they can adjust their position on the field and increase their chances of scoring again. Our studies show that when players feel they have missed their shot, they can trust that feeling and immediately reposition themselves. On the other hand, when basketball players believe they have made a successful shot, our results show that they are better off waiting to see more of the ball's trajectory before making a decision.

Previous studies in laboratory settings showed that metacognitive performance did not differ between visual-only, motor-only, and visuomotor conditions (Arbuzova et al., 2021; Charles et al., 2020). While our results can seem in contradiction, a limitation of our study is that our ecological paradigm did not allow us to control task performance, a well-known confound in metacognitive estimation (Maniscalco & Lau, 2012). Moreover, the ecological context restricted the number of trials we could collect in each condition (see Appendix C), which in turn made the computation of Mratio – the standard measure for assessing metacognitive performance independently of task performance (Rahnev, 2025) – difficult. As participants tended to predict their throws' outcomes more accurately when more visual information was available, our metacognitive effects may therefore be partially explained by task-performance differences.

The second objective of this study was to explore the different facets of metacognition by using different types of judgments. Our data suggest that basketball players assess themselves differently depending on the judgments they make. At the global level, participants were more precise

in their prospective than in their retrospective judgments; this was unexpected based on previous findings from other cognitive domains which showed that participants tended to underestimate their performance in prospective judgments (Kirk et al., 2020; Siedlecka et al., 2016). Although the prediction error did not differ between local and global judgments, we did find differences in bias scores where basketball players overestimated their performance in local judgments but underestimated it in global ones. Local and global judgments may be driven by distinct cues: based on the distinction made by Koriat (2000), we could speculate that local judgments are “experience-based” (based on a feeling emerging during the task; e.g., movement fluency) while global judgments are “information-based” (based on the general knowledge we have of ourselves and the task).

5. Conclusion

In conclusion, these two studies are the first to investigate motor metacognition through retrospective confidence and global judgments in an ecological sports task. This work provides insights into the cues used during the monitoring of sport performance. First, our results observed in Experiment 1, and replicated in Experiment 2, indicate that different information could be used to evaluate free throws depending on the outcome of the throw. Second, we showed that different cues could be used when making local or global (prospective and retrospective) judgments. These data shed theoretical light on sports

metacognition and motor awareness and, more broadly, on the architecture of metacognition. Further work is needed to explore the effects of expertise and multisensory integration in these functions.

Funding acquisition

This work was supported by IDEX Université Grenoble Alpes (grant number ANR-15-IDEX-02) and European Research Council (grant number 803122).

CRediT authorship contribution statement

Lise Brun: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Perrine Porte:** Writing – review & editing, Investigation, Formal analysis. **Marianne Cottin:** Writing – review & editing, Investigation. **Éric Guinet:** Writing – review & editing, Software, Methodology. **Aïna Chala-baev:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Estelle Palluel:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Nathan Faivre:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Céline Souchay:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Appendix A. Appendix A: Frequentist analysis of experiment 1

A.1. Main analysis

We compared the criterion to 0 to investigate the response bias of participants. We found that participants had a significant bias toward responding that the ball was “in” ($M = -0.24$, 95% CI $[-0.34, -0.13]$, $t(38) = -4.53$, $p < .001$).

We performed a mixed-effect logistic regression on the accuracy of the response (correct or incorrect) of the participants, with the confidence, the delay of the visual occlusion, the outcome of the throw, and their interaction as fixed effects. We estimated the optimal random structure based on model comparisons following the procedure of Bates et al. (2015): The selected random effect structure included the main effect of the outcome of the throw, the interaction between the delay and the outcome, and the interaction between the outcome and the confidence.

We first showed that participants were more accurate with more visual feedback ($\hat{\beta} = 0.12$, 95% CI $[0.06, 0.18]$, $z = 4.05$, $p < .001$), and for successful trials compared to failed ones ($\hat{\beta} = 0.91$, 95% CI $[0.49, 1.32]$, $z = 4.30$, $p < .001$). The interaction between the delay of occlusion and the outcome of the throw was significant, indicating that the effect of the visual feedback was stronger in successful than in failed throws ($\hat{\beta} = 0.25$, 95% CI $[0.10, 0.40]$, $z = 3.27$, $p = .001$).

At the metacognitive level, participants were more accurate the more confident they were ($\hat{\beta} = 0.41$, 95% CI $[0.33, 0.50]$, $z = 9.51$, $p < .001$). This effect was moderated by the delay of visual occlusion, indicating that participants adapted better their confidence to the accuracy of their response the more visual information they had ($\hat{\beta} = 0.11$, 95% CI $[0.05, 0.17]$, $z = 3.82$, $p < .001$). The confidence effect was also moderated by the outcome of the throw, indicating that participants adapted their confidence better to the accuracy of their response for failed than for successful throws ($\hat{\beta} = -0.61$, 95% CI $[-0.97, -0.24]$, $z = -3.24$, $p = .001$). Finally, the double interaction between the confidence, the delay of the occlusion, and the outcome of the throw was significant, indicating that better adaptation of the confidence with more visual information was stronger for successful than for failed throws ($\hat{\beta} = 0.22$, 95% CI $[0.11, 0.34]$, $z = 3.78$, $p < .001$).

A.2. Global vs Local judgments

We looked at whether the prediction errors differed between local and global judgments. We observed that participants were more accurate in their global than in their local judgments ($\hat{\beta} = 0.31$, 95% CI $[0.09, 0.53]$, $t(38) = 2.77$, $p = .009$).

We also looked at the difference in terms of bias. We observed that participants overestimated their performance in their local judgments more than in their global judgments ($\hat{\beta} = 0.78$, 95% CI $[0.61, 0.95]$, $t(38) = 9.01$, $p < .001$). Additionally, while the global bias didn't significantly differ from 0 ($M = 0.01$, 95% CI $[-0.27, 0.30]$, $t(38) = 0.10$, $p = .921$), participants overestimated their performance at the local level ($M = 0.79$, 95% CI $[0.42, 1.16]$, $t(38) = 4.31$, $p < .001$).

Appendix B. Appendix B: Additional results

B.1. Sanity check

As the visual occlusion occurred once the ball was thrown, we checked that there was no effect of the visual occlusion delay on performance. It was

the case in both experiments (**Exp.1:** $\hat{\beta} = 0.02 [-0.03, 0.07]$, $BFO = 54.39$; **Exp.2:** $\hat{\beta} = 0.01 [-0.06, 0.08]$, $BFO = 58.39$).

Our main analysis quantified metacognitive performance through the slope of the logistic regression between confidence and prediction accuracy, where accuracy reflects the match between the predicted and actual outcome of the throw. To rule out a potential confounding factor of confidence bias toward one of the option choices (e.g., bias toward being more confident when the shot is predicted to be successful), we ran an additional model with confidence as a function of the predicted outcome, actual outcome, and delay as fixed effects. Random slopes for each of these effects were added. While the evidence was inconclusive in Experiment 1, we observed strong evidence for an absence of confidence bias as a function of the prediction in Experiment 2 (Exp.1: $\hat{\beta} = -0.24 [-0.4, -0.08]$, $BF1 = 2.78$; Exp.2: $\hat{\beta} = -0.1 [-0.33, 0.13]$, $BFO = 11.31$). Additionally, across both experiments, we observed extreme evidence for the interaction between the predicted and actual outcome of the throw (Exp.1: $\hat{\beta} = 0.77 [0.62, 0.91]$, $BF1 > 1000$; Exp.2: $\hat{\beta} = 0.76 [0.55, 0.99]$, $BF1 > 1000$), confirming that confidence tracked the accuracy of the prediction and not just the predicted outcome. Finally, the interaction between predicted outcome, actual outcome, and occlusion delay mirrored the pattern observed in our main analysis (Exp.1: $\hat{\beta} = 0.19 [0.09, 0.28]$, $BF1 = 756.4$; Exp.2: $\hat{\beta} = 0.23 [0.09, 0.36]$, $BF1 = 3.19$), indicating that the better link between confidence and accuracy as visual feedback increased is not attributable to response bias.

B.2. Effect of time

We checked if the observed effect changed across the time course of the experiment.

To do so, we first added the experimental block as a variable in our full model. We found that there was no main effect of the block on accuracy ($\hat{\beta} = 0 [-0.04, 0.03]$, $BFO = 117.97$), no interaction between the delay and the block ($\hat{\beta} = 0 [-0.02, 0.03]$, $BFO = 164.38$), no interaction between the confidence and the block ($\hat{\beta} = -0.03 [-0.06, 0.01]$, $BFO = 30.88$), no double interaction between the confidence, the delay and the block ($\hat{\beta} = 0.01 [-0.02, 0.03]$, $BFO = 132.02$), no double interaction between the delay, the outcome and the block ($\hat{\beta} = -0.02 [-0.06, 0.03]$, $BFO = 59.52$), no double interaction between the confidence, the outcome and the block ($\hat{\beta} = -0.04 [-0.1, 0.03]$, $BFO = 32.15$), and no triple interaction between the delay, the confidence, the outcome and the block ($\hat{\beta} = 0.01 [-0.04, 0.07]$, $BFO = 59.21$). The same results were obtained in Experiment 2. We additionally looked at the effect of trials and observed the same results as with the experimental block in both experiments.

We additionally performed an exploratory analysis, adding the outcome of the previous throw as a predictor in our main model. We observed no main effect of the previous outcome, indicating that it did not impact the prediction accuracy (Exp.1: $\hat{\beta} = 0.05 [-0.14, 0.24]$, $BFO = 17.76$; Exp.2: $\hat{\beta} = -0.13 [-0.42, 0.16]$, $BFO = 9.21$). It also did not influence how confidence tracked the prediction accuracy, with no interaction between the confidence and the previous outcome (Exp.1: $\hat{\beta} = 0.05 [-0.17, 0.26]$, $BFO = 17.12$; Exp.2: $\hat{\beta} = 0.06 [-0.24, 0.37]$, $BFO = 12.22$). While evidence was inconclusive in Experiment 1, in Experiment 2 we observed strong evidence for an absence of interaction between the occlusion delay, the confidence, and the previous outcome (Exp.1: $\hat{\beta} = -0.17 [-0.31, -0.04]$, $BFO = 1.39$; Exp.2: $\hat{\beta} = 0 [-0.22, 0.22]$, $BFO = 18.27$). All other interactions were either inconclusive or supporting the absence of an effect of the previous outcome.

B.3. Effect of demographic variables

We looked at whether our effect varied as a function of the age of the participants. We did so by adding the age as a predictor in our main model. In both experiments, we found evidence for an absence of effect of age.

We also looked at if our effect varied as a function of the sex of the participants. In Experiment 1, we found evidence for an absence of effect of sex. Results were more mixed in Experiment 2: we found a main effect of the sex on the accuracy ($\hat{\beta} = 0.49 [0.15, 0.85]$, $BF1 = 4.88$) indicating that women were more accurate than men, and an interaction between the delay, the outcome and the sex ($\hat{\beta} = 0.84 [0.19, 1.46]$, $BF1 = 3.86$), results for the interaction between confidence and sex, and for the interaction between confidence, outcome, and sex were inconclusive, other results showed evidence for an absence of difference as a function of the sex.

B.4. Expertise effect

We first tested the expertise with the effect of the hours of practice a week, where, in both experiments, we found evidence for an absence of difference.

Then, with the number of years of practice, we also found evidence for an absence of difference.

Additionally, to investigate the expertise at the task more directly, we added the mean performance of participants as a predictor. Again, we found evidence for an absence of difference.

Appendix C. Appendix C: Number of trials per condition

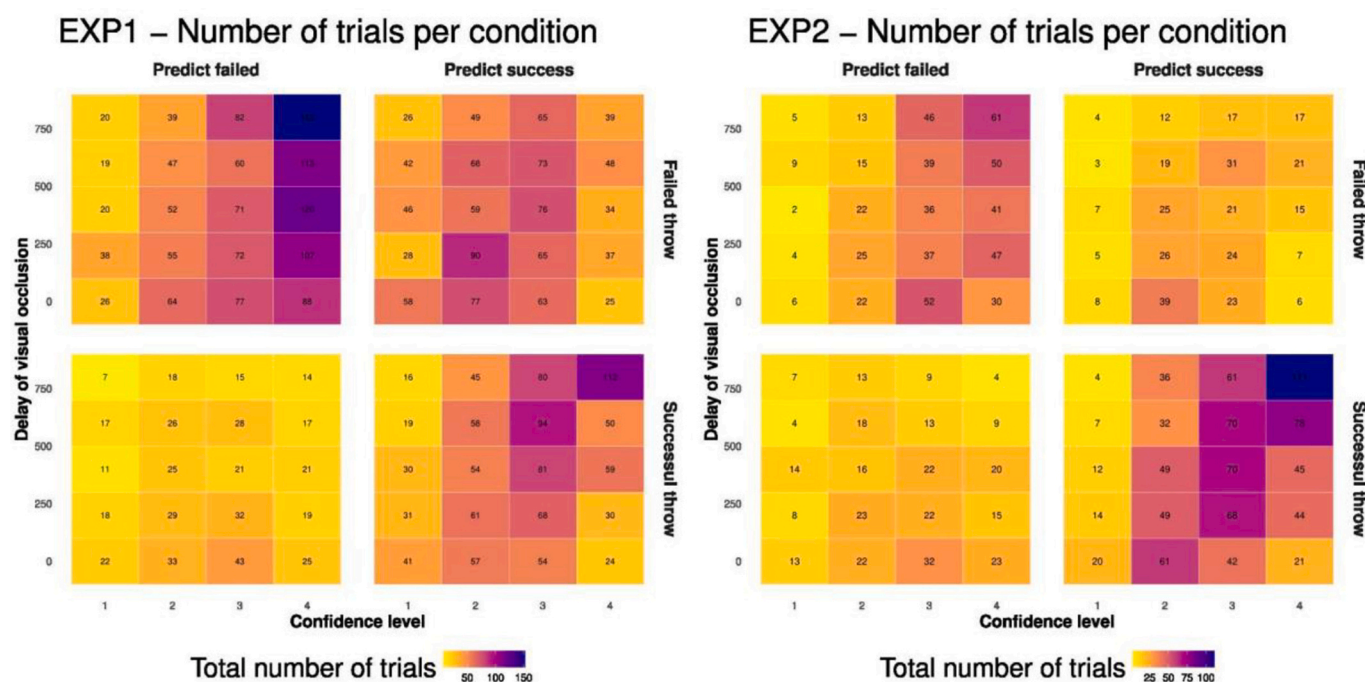


Fig. A1. Number of trials per condition. This figure represents the number of trials for each condition, that is, as a function of the delay of occlusion, confidence level, predicted performance, and outcome of the throw.

Data availability

Data are publicly available on the Open Science Framework platform (<https://osf.io/74s8v/overview>; <https://osf.io/f693p/overview>).

References

- Aglioti, S. M., Cesari, P., Romani, M., & Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. *Nature Neuroscience*, 11(9), Article 9. <https://doi.org/10.1038/nn.2182>
- Arbuzova, P., Peters, C., Röd, L., Koß, C., Maurer, H., Maurer, L. K., ... Filevich, E. (2021). Measuring metacognition of direct and indirect parameters of voluntary movement. *Journal of Experimental Psychology: General*, 150(11), 2208–2229. <https://doi.org/10.1037/xge0000892>
- Bates, D. M., Kliegl, R., Vasishth, S., & Baayen, R. H. (2015). Parsimonious mixed models. *arXiv Preprint arXiv: 1506.04967*.
- Cañal-Bruland, R., Balch, L., & Niesert, L. (2015). Judgement bias in predicting the success of one's own basketball free throws but not those of others. *Psychological Research*, 79(4), 548–555. <https://doi.org/10.1007/s00426-014-0592-2>
- Chancel, M., Filevich, E., & Faivre, N. (2025). Perceptual and attentional uncertainty impact global performance monitoring. *Neuroscience of Consciousness*, 2025(1), Article niaf041. <https://doi.org/10.1093/nc/niab041>
- Charles, L., Chardin, C., & Haggard, P. (2020). Evidence for metacognitive bias in perception of voluntary action. *Cognition*, 194, Article 104041. <https://doi.org/10.1016/j.cognition.2019.104041>
- Culot, C., Notebaert, W., & Gevers, W. (2025). Metacognition in motion : The interplay between motor evidence and visual information in shaping sensorimotor confidence. *Cortex*, 189, 35–49. <https://doi.org/10.1016/j.cortex.2025.05.004>
- Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences*, 4(11), 423–431. [https://doi.org/10.1016/S1364-6613\(00\)01537-0](https://doi.org/10.1016/S1364-6613(00)01537-0)
- Flavell, J. H. (1979). Metacognition and cognitive monitoring : A new area of cognitive-developmental inquiry. *American Psychologist, Psychology and Children: Current Research and Practice*, 34(10), 906–911, 1980–09388-001 <https://doi.org/10.1037/0003-066X.34.10.906>
- Fleming, S. M., Massoni, S., Gajdos, T., & Vergnaud, J.-C. (2016). Metacognition about the past and future : Quantifying common and distinct influences on prospective and retrospective judgments of self-performance. *Neuroscience of Consciousness*, 2016(1), Article niw018. <https://doi.org/10.1093/nc/niw018>
- Frank, D. J., & Kuhlmann, B. G. (2017). More than just beliefs: Experience and beliefs jointly contribute to volume effects on metacognitive judgments. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 43(5), 680–693. <https://doi.org/10.1037/xlm0000332>
- Franklin, B. A., Forgas, M. T., & Hellerstein, H. K. (1978). Accuracy of predicted marathon time: Relationship of training mileage to performance. *Research Quarterly. American Alliance for Health, Physical Education and Recreation*, 49(4), 450–459. <https://doi.org/10.1080/10671315.1978.10615559>
- Hoven, M., Denys, D., Rouault, M., Luigies, J., & Van Holst, R. (2022). How do confidence and self-beliefs relate in psychopathology: A transdiagnostic approach. *Biological Psychiatry*, 91(9), S273. <https://doi.org/10.1016/j.biopsych.2022.02.695>
- Jagacinski, R. J., Isaac, P. D., & Burke, M. W. (1977). Application of signal detection theory to perceptual-motor skills: Decision processes in basketball shooting. *Journal of Motor Behavior*, 9(3), 225–234. <https://doi.org/10.1080/00222895.1977.10735113>
- Joch, M., Hegele, M., Maurer, H., Müller, H., & Maurer, L. K. (2017). Brain negativity as an indicator of predictive error processing: The contribution of visual action effect monitoring. *Journal of Neurophysiology*, 118(1), 486–495. <https://doi.org/10.1152/jn.00036.2017>
- Kelemen, W. L., Frost, P. J., & Weaver, C. A. (2000). Individual differences in metacognition: Evidence against a general metacognitive ability. *Memory & Cognition*, 28(1), 92–107. <https://doi.org/10.3758/BF03211579>
- Kirk, T., Haeghele, J. A., & Zhu, X. (2020). Performance calibration among youth with visual impairment on a 6-minute endurance run test. *British Journal of Visual Impairment*, 38(3), 324–332. <https://doi.org/10.1177/0264619620912768>
- Koriat, A. (2000). The feeling of knowing: Some metatheoretical implications for consciousness and control. *Consciousness and Cognition*, 9(2), 149–171. <https://doi.org/10.1006/ccog.2000.0433>
- Kumawat, A. S., Manson, G. A., Welsh, T. N., & Tremblay, L. (2022). Detecting endpoint error of an ongoing reaching movement: The role of vision, proprioception, and efference. *Journal of Motor Behavior*, 54(4), 457–465. <https://doi.org/10.1080/00222895.2021.2013767>
- MacIntyre, T. E., Igou, E. R., Campbell, M. J., Moran, A. P., & Matthews, J. (2014). Metacognition and action: A new pathway to understanding social and cognitive aspects of expertise in sport. *Frontiers in Psychology*, 5. <https://www.frontiersin.org/articles/10.3389/fpsyg.2014.01155>
- Maglott, J. C., Chiasson, D., & Shull, P. B. (2019). Influence of skill level on predicting the success of one's own basketball free throws. *PLoS One*, 14(3), Article e0214074. <https://doi.org/10.1371/journal.pone.0214074>
- Maglott, J. C., & Shull, P. B. (2019). *Wearable occlusion device for assessing cognitive basketball shooting performance between males and females*. Proceedings of the International Conference on Industrial Control Network and System Engineering Research (pp. 37–41). <https://doi.org/10.1145/3333581.3333599>
- Maniscalco, B., & Lau, H. (2012). A signal detection theoretic approach for estimating metacognitive sensitivity from confidence ratings. *Consciousness and Cognition*, 21(1), 422–430. <https://doi.org/10.1016/j.concog.2011.09.021>
- Maurer, L. K., Maurer, H., & Müller, H. (2015). Neural correlates of error prediction in a complex motor task. *Frontiers in Behavioral Neuroscience*, 9. <https://www.frontiersin.org/articles/10.3389/fnbeh.2015.00209>
- Mazancieux, A., Pereira, M., Faivre, N., Mamassian, P., Moulin, C. J. A., & Souchay, C. (2023). Towards a common conceptual space for metacognition in perception and memory. *Nature Reviews Psychology*, 2(12), 751–766. <https://doi.org/10.1038/s44159-023-00245-1>

- Morey, R. D., & Rouder, J. N. (2012). *BayesFactor : Computation of Bayes Factors for Common Designs* (p. 0.9.12–4.7) [Jeu de données]. <https://doi.org/10.32614/CRAN.package.BayesFactor>
- Nelson, T. O., & Narens, L. (1990). Metamemory : A Theoretical Framework and New Findings. In , 26. *Psychology of Learning and Motivation* (pp. 125–173). Elsevier. [https://doi.org/10.1016/S0079-7421\(08\)60053-5](https://doi.org/10.1016/S0079-7421(08)60053-5).
- Rahnev, D. (2025). A comprehensive assessment of current methods for measuring metacognition. *Nature Communications*, 16(1), 701. <https://doi.org/10.1038/s41467-025-56117-0>
- Rahnev, D., Desender, K., Lee, A. L. F., Adler, W. T., Aguilar-Lleyda, D., Akdoğan, B., ... Zylberberg, A. (2020). The confidence database. *Nature Human Behaviour*, 4(3), 3. <https://doi.org/10.1038/s41562-019-0813-1>
- Rieser, J. J., Erdemir, A., Khuu, N.-T., & Beck, S. (2014). Knowing the results of one's own actions without visual or auditory feedback when walking, throwing, and singing. *Ecological Psychology*, 26(1–2), 134–146. <https://doi.org/10.1080/10407413.2014.875318>
- Rouault, M., & Fleming, S. M. (2020). Formation of global self-beliefs in the human brain. *Proceedings of the National Academy of Sciences of the United States of America*, 117(44), 27268–27276. <https://doi.org/10.1073/pnas.2003094117>
- Seow, T. X. F., Rouault, M., Gillan, C. M., & Fleming, S. M. (2021). How local and global metacognition shape mental health. *Biological Psychiatry*, 90(7), 436–446. <https://doi.org/10.1016/j.biopsych.2021.05.013>
- Siedlecka, M., Paulewicz, B., & Wierzchoń, M. (2016). But i was so sure! Metacognitive judgments are less accurate given prospectively than retrospectively. *Frontiers in Psychology*, 0. <https://doi.org/10.3389/fpsyg.2016.00218>
- Souchay, C., Isingrini, M., & Gil, R. (2006). Metamemory monitoring and Parkinson's disease. *Journal of Clinical and Experimental Neuropsychology*, 28(4), 618–630. <https://doi.org/10.1080/13803390590935453>
- Williams, A. M., & Jackson, R. C. (2019). Anticipation in sport: Fifty years on, what have we learned and what research still needs to be undertaken? *Psychology of Sport and Exercise*, 42, 16–24. <https://doi.org/10.1016/j.psychsport.2018.11.014>
- Zampieri, F. G., Casey, J. D., Shankar-Hari, M., Harrell, F. E., & Harhay, M. O. (2021). Using Bayesian methods to augment the interpretation of critical care trials. An overview of theory and example reanalysis of the Alveolar Recruitment for Acute Respiratory Distress Syndrome Trial. *American Journal of Respiratory and Critical Care Medicine*, 203(5), 543–552. <https://doi.org/10.1164/rccm.202006-2381CP>