Measuring Conscious Monitoring and Metacognition of Motor Performance at the Start, Middle, and End of a Reaching Movement

by

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Abstract

The ability to monitor our arm position during goal-directed behaviour allows us to bring our limb to a target as accurately as possible. Despite our success in executing accurate movements, some work suggests that individuals have limited access to information about their limb position (Fourneret & Jeannerod, 1998; Pélisson, et al., 1986). However, contradictory evidence from metacognition research indicates that people have some access to details about their movements. In these studies, individuals are asked to rate their confidence after making judgements about their movements and tend to give higher confidence ratings when they are correct, showing some capacity for self-monitoring (Arbuzova et al., 2021). These conflicting results suggest that we may not be monitoring an entire movement from start to end.

In the current study, participants (n=50) made reaching movements toward targets on a screen. They were then presented with two movement paths: one being their actual trajectory and the other being a visually deviated version. Here, we manipulated the location that the deviation was implemented (i.e., start, middle, or end of the path). Participants were then asked to determine which trajectory was their own, while also rating their confidence in their response.

Overall, accuracy was lower than expected. Nevertheless, accuracy was significantly lower when deviations occurred at the start of the reach, indicating that awareness of limb position is further reduced at the start of a movement. Additionally, participants showed some ability to metacognitively monitor their movements because their confidence scaled with their accuracy in the task. Finally, differences in metacognitive processes between locations were found, with higher average confidence in the middle of a movement when accuracy was held constant.

We conclude that people have a remarkable blindness to the properties of their own movements, while still having a “feel” of their performance. As well, poor awareness of limb position at the start of a movement suggests reduced attention to the limb at this time, possibly due to movement programming demands.

Preface

This thesis is an original work by Gabriela Oancea. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name “Measuring conscious monitoring and metacognition of motor performance at the beginning, middle, and end of a reaching movement”, No. Pro00128064, March 16, 2023. No part of this thesis has previously been published.

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1. Introduction

When reaching for objects in our daily activities, such as picking up a coffee cup, the brain must rapidly process visual information, plan the trajectory, and then execute the motor commands in order to guide the hand towards the target. It seems logical to assume that since we have privileged access to information about our own body and self, we would at least be aware of the position of our limbs in space. However, it is well established that we may remain largely unaware of motor control processes as they occur unconsciously or without explicit monitoring (Blakemore & Frith, 2003; Haggard, 2001). For instance, we may not be aware of the activation of motor units or other specific visuomotor processes that are generated by the central nervous system to execute the movement. Indeed, experimental evidence suggests that humans have relatively low access to details of voluntary movements such as limb position, movement adjustments, and motor commands (Charles et al., 2020).

How is precise motor control achieved without awareness? To optimize motor control and learning, it has been proposed that the central nervous system (CNS) contains forward models which allow us to predict the behaviours of our body and the world (Wolpert & Ghahramani, 2000). Forward models use efference copies, which are copies of the motor commands that are issued to make a movement, in order to predict the sensory consequences of an unfolding action (Wolpert et al., 1995). Sensory feedback, such as visual information about the environment and proprioceptive information about where our body is in space, is relayed back to the CNS for comparison. If there is a discrepancy between the predicted state and the actual sensory feedback coming from the movement, this error will be detected and the movement will be updated. However, it seems that the actual state of the motor system, the actual sensory consequences of a movement, and the computations behind the forward model are normally unavailable to awareness as long as the desired goal is achieved (Blakemore et al., 2002). This lack of awareness is evident by target jump experiments using the double-step paradigm (see Pélisson, et al.,1986; Prablanc & Martin, 1992; Goodale et al., 1986). These experiments have consistently shown that individuals can adjust their limb to correct for an imperceptibly displaced target jump, implying a separation between conscious awareness and visuomotor control. Such a dissociation is in line with the two visual streams hypothesis proposed by Goodale & Milner in 1992, which suggests that there are distinct processes supporting vision for perception and vision for action. The dorsal stream mediates the visual control of movement, while the ventral stream is involved with perception and object recognition and is typically associated with visual information that is available for conscious report. Notably, the dorsal stream relies on rapid feedforward mechanisms to convert moment-to-moment information about the position of objects into the coordinate frames relative to the effector, and is not dependent on conscious perception (Goodale, 2008). Hence, some information, which is unavailable to the ventral stream, is available to the motor-oriented dorsal stream.

Even more evidence for the limited awareness of movement details comes from an experiment by Fourneret and Jeannerod (1998), where participants drew sagittal lines on a tablet with a stylus and had no visual information about their arm or hand. On some trials, a significant visual deviation was imposed resulting in the participant's viewed trajectory to deviate to the right or the left of their actual movement by a variable angle as the line was being drawn. The desired result of drawing a straight line could still be achieved by making deviant movements to compensate for the perturbation. After each trial, participants were shown a card with 13 lines drawn at different angles from a starting point. They were asked to choose a line that corresponded to the trajectory of their hand movement rather than the line that appeared on the screen. Participants consistently underestimated the deviation of their hand trajectory because they tended to select a line that was straighter than the actual path they were making. Indeed, previous research suggests that upper limb reaching movements in the horizontal plane appear to be planned in order to generate straight line paths in visually perceived space (Flanagan & Rao, 1995). That is, individuals are biased to make straight line paths in visually perceived hand space even when a perturbation is introduced that causes hand paths in Cartesian space to be curved. However, the results from Fourneret and Jeannerod (1998) also suggests that humans are relatively unaware of the way they move, even when performing a seemingly simple task such as drawing a straight line. It seems that unless there is a significant discrepancy between an internal prediction of the movement and the actual sensory consequences, we remain unaware of the features of an ongoing movement (Castiello et al. 1991; Pacella & Moro, 2022).

Given that we can achieve precise motor control through internal representations of our body and the environment which are typically unavailable to awareness (Naranjo & Schmidt, 2012), it may be unnecessary to evaluate the outcomes of our actions in “normal” everyday movements when the environment is highly predictable and stable (i.e., closed motor skill, see Knapp, 1970). For instance, when reaching to pick up a cup of coffee it is unlikely that any significant perturbations will occur to the limb or the target, and any small errors in the limb’s trajectory can be corrected online. Moreover, previous work using the double-step paradigm and Fourneret and Jeanerod’s experiment have involved relatively small perturbations that participants did not consciously perceive, and therefore demonstrated low awareness because their goal was achieved. However, in open motor skills (e.g., tennis, soccer, basketball) athletes must react in a dynamically changing and unpredictable environment which can lead to large discrepancies between actual and predicted limb position. As such, performance monitoring becomes valuable in detecting any errors and subsequently making corrections to ensure that the original goal is accomplished. In addition, monitoring performance is useful when learning a new skill to detect and evaluate errors as well as update internal representations of the movement for future use (Song, 2019). For instance, when first learning a tennis forehand, we monitor our swing, the trajectory of the ball, and where it lands to ensure that the ball contacts the racket at an optimal point and the ball lands inside the court. Accuracy alone can lead to success in a single shot, but consistent performance requires evaluating the outcomes of movements to understand the necessary mechanics contributing to their success.

This suggests that the ability to monitor the accuracy of movements is a key component of motor learning and performance. Indeed, there has been a growing body of research assessing what is being called the metacognition of action. In general, metacognition refers to the ability to monitor one's own cognitive processes, and a common operationalization of metacognitive ability is an individual's confidence reports about their accuracy in a detection or discrimination task (Fleming & Lau, 2014). That is, individuals provide judgements about how confident they are regarding the correctness of their decisions after each trial (Maniscalco & Lau, 2012). With respect to motor metacognition, observers are typically asked to perform a movement and make a perceptual judgement about their limb position or movement trajectory (see Arbuzova et al. 2021; Charles et al., 2020; Pereira et al., 2023; Verrel et al., 2023; Bègue et al., 2018). Metacognitive ability is assessed by determining how well an individual is able to distinguish between correct and incorrect judgements using their confidence ratings. Research in the field of metacognition supports the general idea that when one is confident, one is more likely to be correct (Fleming & Lau., 2014). When this alignment is true, it is taken as evidence that people have metacognitive access to the underlying process for which they are reporting confidence judgments. An observer that gives high confidence ratings when they successfully detect/discriminate stimuli and gives low confidence ratings when they do not detect/discriminate stimuli will have high metacognitive sensitivity. On the other hand, an observer whose confidence ratings do not scale with their ability to detect/discriminate stimuli will have a low metacognitive sensitivity.

Using confidence to accurately measure metacognition can be explained by models of decision making. In the process of decision making, humans are often faced with a choice of selecting one action among several other choices (Yeung & Summerfield., 2012). Not only do we make decisions, but we also evaluate the outcomes of those decisions to determine if they will result in favourable or unfavourable outcomes. According to accumulation-based models of decision making, deciding whether to gather more information from the environment before making a choice relies on whether the level of accumulated evidence has reached a particular threshold (Desender et al., 2018; Wispinski et al., 2022). When evidence from the environment strongly favours one option, accuracy will be high (Kiani & Shadlen, 2009). It is theorized that the accumulated evidence is also related to one's confidence level, with confidence increasing as the amount of evidence increases (Kiani & Shadlen, 2009). When evidence from the environment is uncertain or lacks reliability which results in less accumulation, confidence will be low (Desender et al., 2018). Therefore, because accuracy and confidence are correlated (Kiani & Shadlen, 2009), confidence provides a direct but imperfect measure of an individual's decision-making processes (De Martino et al., 2013; Maniscalco & Lau, 2012; Pasquali et al., 2010).

In general, metacognition research has shown that – despite the earlier discussion around a lack of awareness of properties of motor control – people *can* appropriately monitor their visuomotor performance. In a recent study by Arbuzova et al. (2021), participants performed a semi-virtual task in which they were asked to throw a virtual ball towards a target, and then make a two-alternative forced choice (2AFC) based on the resulting ball trajectory. One trajectory corresponded to their actual movement and the other deviated from the one they produced. Participants were asked which trajectory was their own, and to rate their confidence in their response. Arbuzova et al. observed that participants were able to effectively monitor their own movements because their confidence judgements aligned with their accuracy in the task. This result is consistent with other research (Sinanaj et al., 2015; Verrel et al., 2023) showing that healthy observers can typically monitor movement trajectories to some extent. In addition to successful monitoring of movement trajectories, Pereira et al. (2023) showed that participants were able to metacognitively monitor the presence of deviations in their movements, even without consciously perceiving these deviations. In this study, participants performed a task in which they had to reach to a target on a screen, by using a joystick to control a cursor. On some trials, a deviation in the mapping between the joystick and the cursor was introduced on either the right or the left side. Participants were told to correct for these deviations when they occurred, as well as report any deviations and rate their confidence in their judgement after every trial. The results showed that although participants successfully corrected for the deviations without being aware of them, their metacognitive efficiency was not impaired by their lack of awareness. That is, metacognitive efficiency was similar when participants reported deviations and when they did not, suggesting that even if the visuomotor information was not enough to report a deviation, it could still be used to rate confidence.

One important consideration of previous work on motor metacognition is the timing or location of the deviations introduced. This is because we may not be monitoring our entire movement from start to end, given the limited processing capacity of the brain during rapid dynamic movements (Wolpert et al., 1995). Returning to the example of reaching for a coffee cup, it seems possible that we may only be consciously aware of the start (i.e., the position of the hand before the movement begins) and the result (i.e., whether we successfully grasp the cup), rather than the adjustments that occur in the middle of a movement (Blakemore et al., 2002). In addition, it is well established that different components of a movement have different control mechanisms (see Elliott et al., 2010, 2017), yet, to our knowledge, no studies have investigated whether humans are more *aware* of their movements at certain stages. Further, there is evidence that certain stages of a movement show heightened visuomotor sensitivity. For instance, Tremblay et al. (2017) had participants perform reaches to targets while being provided with several brief windows of vision at different time points. In one experiment, participants made a 2AFC as to whether their limb overshot or undershot the target. The results revealed that the judgement of endpoint bias was most accurate when vision was provided relatively early in a reaching movement, suggesting that perceptual sensitivity may be enhanced at the start of a movement. In another experiment by de Brouwer et al. (2018), participants made goal-directed reaches without visual feedback of their arm, and their hand position was represented as a cursor. The authors manipulated the location that participants fixated their gaze while correcting for visual displacements of the cursor. The authors found that corrections were faster and more accurate when gaze was directed at the reach target compared to any other location, implying that visual information coming from the endpoint of a reach is particularly important to make movement corrections. Another rationale for considering the timing/locations of deviations is that attention also varies across different stages of a goal-directed movement (Posner & Keele, 1969; Khan et al., 2006), so differences in awareness and monitoring may emerge based on when these resources are “free” for limb position estimation. Finally, previous metacognition studies have employed tasks such as semi-virtual ball throwing and joystick movements. We feel it is crucial to investigate metacognition of more naturalistic movements, like goal-directed reaches, as these are movements performed frequently in everyday life such as when eating food or using tools.

More broadly, motor awareness and action metacognition of naturalistic upper-limb movements is also an important line of research because several disorders are known to affect these mechanisms. At the level of motor control, Huntington’s disease is a neurologic disorder resulting in damage to the basal ganglia (Aylward et al., 1997). Patients with this disorder take longer to detect and correct errors, suggesting a deficit in error feedback control (Say et al., 2011). Other disorders involving damage to the basal ganglia such as Parkinson’s disease may also show reduced sensitivity to detect changes in limb position and have impairments in feedback-based error monitoring (Fasano et al., 2022). Further, limb apraxia (LA) is a disorder of higher motor control that is characterized by perceptual, motor, and cognitive deficits and is associated with damage of left frontoparietal brain networks (Spinelli et al., 2022). Consequently, patients with LA are known to display deficits in action execution as well as action monitoring, resulting in problems evaluating the outcomes of their actions. Moving on from motor control disorders to those where motor awareness or metacognition of action may be impaired, schizophrenia is a mental illness where patients often have an abnormal experience of their own actions (Voss et al., 2010). In some cases, a patient may feel like their actions are not being executed by themselves, but by an external source. This phenomenon is thought to arise from a lack of awareness of predicted limb position and predicted consequences of a movement (Blakemore et al., 2002). Investigating what constitutes “normal” awareness and metacognitive monitoring in healthy participants can therefore shed light on processes that are impaired in patients with the above-mentioned disorders.

Therefore, the aim of this study was to determine if people are aware of the trajectory of their hand when making a goal-directed reach, and whether this awareness changes between different stages of a movement (e.g., do you have more awareness at the start, middle or end of a movement). Here, we use the term “awareness” to refer to motor awareness, which is defined as the awareness of one’s motor state while executing a movement (Pacella & Moro, 2022). Then, layering in our interest in metacognition, another goal was to explore metacognitive monitoring of the limb at these different stages. To accomplish this, following a reaching movement, we showed participants trajectories of their own movements along with visually deviated ones and had them make a decision on which trajectory they thought was their own, followed by rating their confidence in that judgement. To isolate awareness and monitoring at different stages of the reach, the visual deviation occurred at the start, middle, or end of the deviated trajectory.

We predict that overall awareness, defined as participants’ ability to discriminate between their own movement and a deviated one irrespective of the deviation’s location, will be low. This hypothesis is based on the results of Fourneret and Jeannerod’s (1998) study, research using the double-step paradigm, and the two visual streams hypothesis. Together, they show that information about movement details can remain outside of conscious awareness. As such, we expect that participants will be able to make accurate reaches towards the targets but have difficulty identifying which trajectory is their own after producing the movement. However, we acknowledge that currently there is no consensus on the threshold at which a perturbation should be considered easy or difficult to detect. Previous research in other domains has shown that individuals are not sensitive to detecting a shift in target position of several centimeters (e.g., Goodale et al., 1986), or a deviation of their limb trajectory by 10 degrees (Fourneret & Jeannerod, 1998), but we can only speculate on what constitutes good or poor performance in the current task.

Our second prediction is that awareness (quantified as the ability to detect the real trajectory from the deviated one), though low overall, will be greater when the deviation is imposed at the start and end of a movement compared to the middle. This hypothesis is based on prior work showing evidence for increased visuomotor sensitivity near movement initiation and endpoint (e.g., Tremblay et al., 2017; de Brouwer et al., 2018). We can also speculate that the results of Fourneret and Jeannerod (1998), who consistently introduced the deviation in the middle of the trajectory, may have shown poor accuracy because awareness of the limb is significantly reduced at this time.

Lastly, with respect to metacognition we hypothesize that participants will be able to metacognitively monitor decisions about their movements to some extent, meaning that their confidence judgements about which trajectory corresponded to their movement would scale with their overall accuracy. Indeed, previous research on motor metacognition has shown that participants confidence ratings aligned with their accuracy when discriminating between trajectories (e.g., Arbuzova et al., 2021; Verrel et al., 2023; Bègue et al., 2018) or detecting visuomotor deviations (Pereira et al., 2023). However, we expect that metacognitive monitoring at each location will correspond with awareness at each location, where participants will monitor their movements to a greater extent at the start and the end compared to in the middle. We have not come across any previous metacognition work that manipulated deviation location, and there is no indication suggesting that metacognitive ability would be different than awareness at different movement stages.

2. Methods

2.1 Participants

50 neurologically healthy self-reported right-handed participants with self-reported normal or corrected-to-normal vision (34 females, 16 males, M = 19.3 years, SD = 3.0 years) completed the experiment. The experiment took place over one session lasting approximately 50 minutes. Participants were compensated $10 CAD or one credit depending on how they were recruited. All participants provided written informed consent and all protocols were approved by the University of Alberta research ethics board.

2.2 Apparatus

Participants sat on a chair in front of a table (76 cm high). Located beneath the surface of the glass tabletop, a TV (*L* 109 cm, *W* 61 cm) with a monitor resolution of 1920 by 1080 pixels was centred along the mid-sagittal axis. The TV displayed stimuli such as the home position, targets, trajectories, and responses. Finger movements were recorded using infrared cameras (OptiTrack Flex 13, NaturalPoint Inc., Corvallis, OR, USA) which monitored the position of a reflective marker in 3D space (x, y and z axes) at a frequency of 120 frames per second. Markers were taped to the dorsal side and distal portion of the participant's right index finger. The experimental procedures and equipment were controlled using custom MATLAB scripts (The MathWorks Inc., Natick, MA, USA) which gathered the Optitrak data and controlled the display via Psychtoolbox (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007).

2.3 Procedure

Trials consisted of a reaching portion and a judgment portion. The reaching portion began with participants putting their right index finger on an 8.5 cm by 8.5 cm (150 p by 150 p) grey square at the bottom of the display (i.e., home position) (see Figure 1A). At this time, a second 8.5 cm by 8.5 cm (150 p by 150 p) grey square (i.e., target) appeared at approximately 50 cm of distance in the sagittal direction (see Figure 1A). To prevent participants from repeating the same movement in each trial, the location of both the home position and target varied between each trial. That is, the horizontal distance of the home position and target moved +/- 26 cm from the midline, while the vertical position remained the same for each trial. Upon presentation of the target, participants were instructed to reach to the target as fast and as accurately as possible. At the end of each reach, when the target was touched, it and the home position disappeared and a grey bar (109 by 8.5 cm or 1920 by 150 p, see Figure 1A) appeared along the bottom of the screen. Participants ended the reach portion of the trial by bringing their finger back to the bottom of the screen, touching anywhere along the grey bar. This served to move participants' fingers away from the target position and out of the way so that the view of the screen was not obstructed.

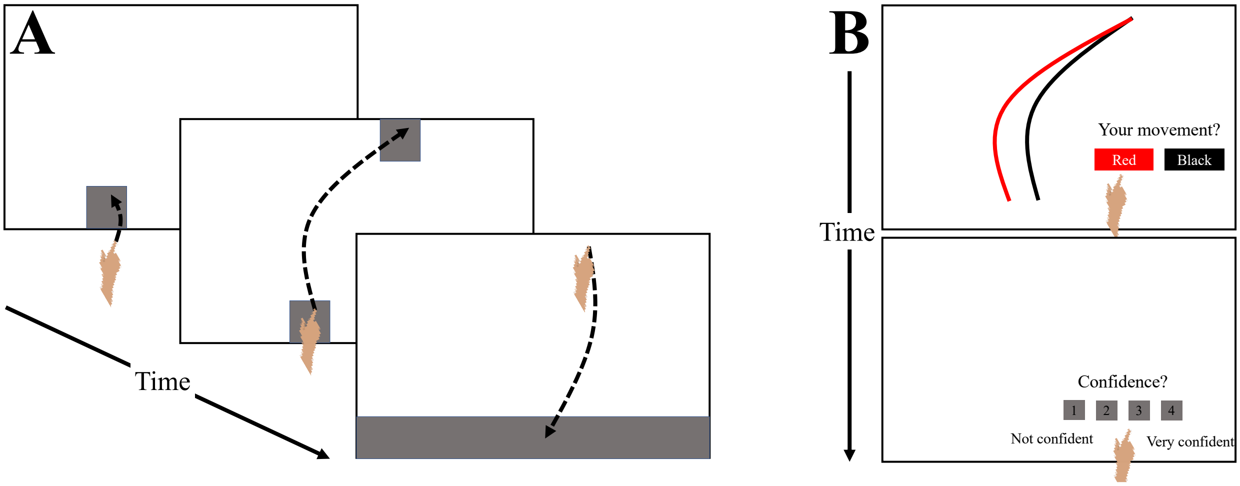

Figure 1. Sequence of events for a representative single trial. (A) Reaching portion. Following the presentation of the home position, participants put their finger inside the square, which triggered the target to appear. They then reached to the target, and the home position and target

immediately disappeared while the grey bar appeared. Participants then returned their hand to the bottom of the screen, touching anywhere inside the grey bar. (B) Judgement portion. At this point, two trajectories were presented on the screen and participants decided which trajectory they thought was their own by pressing “red” or black”. After their response, a confidence rating scale from 1 to 4 appeared. Immediately after selecting a confidence rating, the home position for the next trial was presented.

Immediately upon completion of the reach portion of the trial participants were asked to make two consecutive judgements – a path judgement and a confidence judgement (see Figure 1B). First, for the path judgment, two trajectories appeared on the screen, one being red and the other black (see Figure 1B). One trajectory was the actual projected path that participants had made from the home position to the target as recorded by the reflective markers and cameras, while the other trajectory was an “artificial” path that was visually deviated to the left or right. To be clear, the reach was conducted in full three-dimensional (3D) space (e.g., participants were free to lift their hand) and the visual representation was the projection of this 3D trajectory to the two-dimensional plane of the table. The specific part of the projected path that was shown was from the time after the hand had originally reached the start position. Then, from this time, this path consisted of all points between the last recorded frame where the projected path fell within the start position until the first recorded frame where it fell within the target. The experimental manipulation consisted of deviating the participant’s original trajectory at either the start, the middle, or the end. In order to make perturbations at a consistent point in space (e.g., the actual middle) it was necessary to space-normalize each projected path to the reach-distance dimension (for details see Gallivan & Chapman, 2014). This yielded a space-normalized trajectory for every projected path with 100 points equally divided across reach distance (therefore, approximately every 5 mm of distance between the bottom and top of the screen). Due to recording errors (e.g., the transient detection of an erroneous motion capture marker due to reflection etc.) some projected paths were discarded and trials were repeated before the judgement phase. These errors were detected by looking for projected paths that reversed direction (went toward the start position rather than the target position) at any point and occurred on an average of 10% of trials (36.2 times per 360 trial session). To perturb trajectories at the start or end (see Figures 2A and 2C respectively), a transformation was calculated that shifted the start or end of the actual reach by the desired number of pixels while shifting the opposing end point (end or start) by 0 pixels. Then a linear interpolation was applied to calculate the shift for all other points on the actual trajectory. As an example, a 20 pixel shift to the start position meant that, relative to the actual trajectory, the artificial trajectory was shifted 20 pixels at the start, 15 pixels 25% of the way through the reach, 10 pixels at the midway point, 5 pixels 75% of the way through the reach and 0 pixels at the end (see Figure 2A). To construct the ‘middle’ perturbations we introduced an arc that followed the shape of a gaussian distribution between -1 and 1 standard deviation (STD). This meant the middle perturbations were 0 pixels at the start and end of the reach and shifted by the specified amount in the middle of the reach. The intermediate perturbation values (e.g., start to middle and middle to end) followed the shape of a gaussian between +/- 1 STD (see Figure 2B).

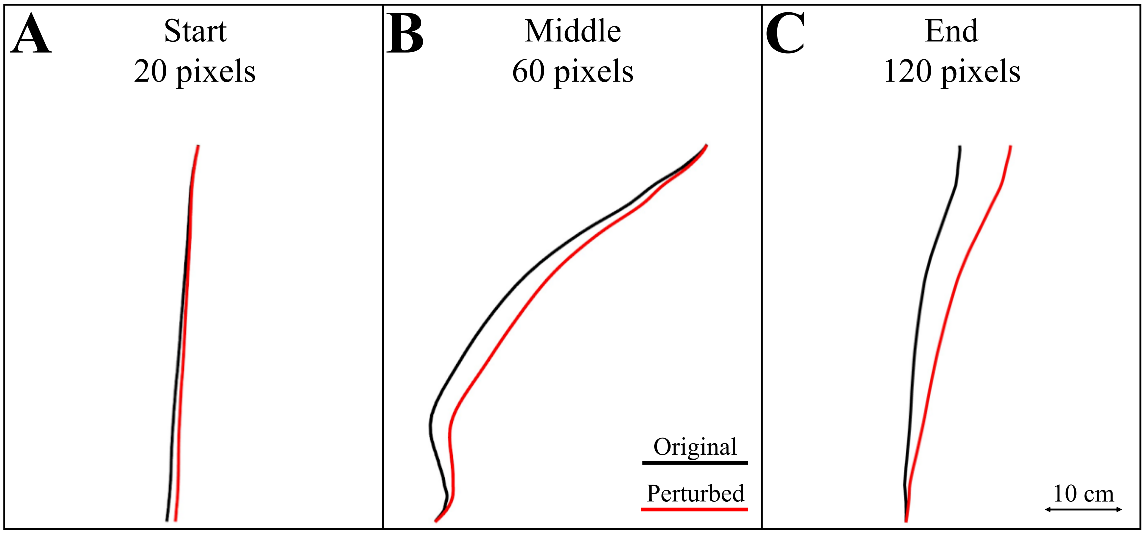

Figure 2. Examples of original (black) and perturbed (red) trajectories perturbed 20 pixels/ 1.1 cm at the start (2A), 60 pixels/ 3.4 cm in the middle (2B), and 120 pixels/ 6.8 cm at the end (2C). All examples are trajectories perturbed to the right side. In the actual experiment whether the original trajectory was black or red was randomly selected each trial, as was the side of the perturbation.

When presented with the artificial and actual trajectories (one red, one black, color randomly assigned each trial), participants had to make the path judgment to determine which trajectory they thought was their own by choosing the red or the black line (i.e., discrimination task) (see Figure 1B). This was done by pressing either “red” or “black” on the screen, presented as 23 cm x 8 cm buttons located at the bottom right corner of the screen. Once participants made their path judgement response, they were immediately presented with the confidence judgment. Here, participants rated their confidence in their own path judgment on a scale ranging from 1 = not confident to 4 = very confident (i.e., metacognition task) (see Figure 1B) by pressing either 1, 2, 3, or 4 (6 cm x 6 cm buttons) on the bottom right of the screen. The next trial started immediately following the confidence rating by showing the home position for the next trial on the screen. The experiment was self-paced in that participants could wait as long as they wanted before bringing their hand to the start position. Participants did not receive feedback about their accuracy.

Task difficulty on each trial (i.e., the implemented visual deviation) was chosen based on the method of constant stimuli. This method involves determining several stimulus levels and presenting each level many times in a random order (Simpson, 1988). In the current study, there were 6 different levels of perturbation: 20, 40, 60, 80, 100, and 120 pixels. (1.1 cm, 2.3 cm, 3.4 cm, 4.6 cm, 5.7 cm, 6.8 cm). Each level was presented 10 times on both the right and the left sides as well as at each of the 3 movement locations, resulting in a total of 360 trials. We used the method of constant stimuli to ensure that there were an equal number of responses at varying levels of stimuli. The deviation was intended to assess participants' general ability/accuracy at this task, that is, to gauge their awareness of the movement they had just executed. The deviation was also used to determine whether participants were better able to discriminate between their own movement and an artificial one at certain stages of their reach (i.e., start, middle, and end), as well as to determine whether confidence ratings would change during these stages. The experiment was organized into 6 blocks of 60 trials and the total duration of the experiment lasted approximately 50 minutes. Participants were given 10 practice trials where performance was not recorded to become comfortable with the experimental setup.

2.4 Data Analyses

Before we can assess metacognitive ability, we first need accuracy in a discrimination task and the subsequent confidence reports. These measures can then be used to determine how well participants can match their feelings of confidence to their actual performance, which is also known as metacognitive sensitivity, our analysis of which is described below. In the current study, we manipulated the location, size, and side of a visual perturbation to a projected reach. Accuracy was defined as the proportion of correct trials for a given combination of experimental factors while confidence was determined by the participants' average confidence ratings for that set of factors. To look for changes in accuracy across our experimental conditions, performance was submitted to a 3 location (start, middle, and end) by 2 side (right and left) by 6 perturbation-amount (20, 40, 60, 80, 100, and 120 pixel) repeated measures (RM) ANOVA. This way, we could assess how participants' accuracy changed at the 3 locations of perturbation as well as how it changed with increasing stimulus intensities. This also allowed us to determine whether participants were better able to discriminate between trajectories when the deviation was on the right or the left side. We also subjected the confidence ratings to the same 3 location (start, middle, and end) by 2 side (right and left) by 6 amount (20, 40, 60, 80, 100, and 120 pixel) RMANOVA to investigate how participants' feelings of confidence changed at different locations of the deviation and different stimulus intensities, and whether the side that the deviation was presented on mattered.

To assess metacognitive performance, we conducted two additional analyses. Before describing them, it is important to note a key limitation of this study. An accurate assessment of metacognition, like the best psychometric tests, ideally relies on having many (e.g., hundreds or thousands) of samples presented for each combination of experimental factors. We are clearly very short of this goal having presented only 10 trials within each specific condition. That being said, with a healthy sample size of 50 participants we do feel the following tests allow us to draw some general conclusions about metacognitive performance in this naturalistic reaching task which point to exciting areas of future work. With that caveat aside, to test for overall signs of metacognitive sensitivity we compared confidence judgements on trials where participants were accurate (got the discrimination correct) to confidence judgments on trials where they were inaccurate (got the discrimination wrong). To better account for individual differences in how participants used the confidence scale, for these analyses we computed confidence as the proportion of trials in which the participant used high confidence ratings. What constituted a high confidence rating was determined for each individual by finding whichever level of the scale gave the closest to an even split of their data. Then, this proportion high-confidence was subjected to a 3 location (start, middle, and end) by 2 side (right and left) x 2 accuracy (correct and incorrect) RMANOVA. Notably we had to collapse across the levels of perturbation-size in order to have enough data to run this analysis. Although this choice increases trial counts, it potentially introduces performance confounds into the confidence data due to the influence of perturbation-size on task performance. A significant interaction between location and accuracy would be taken as a sign that metacognition was not operating the same at each location and was followed up by comparing the difference between proportion high-confidence on correct and incorrect trials across the three locations.

Given that task performance (i.e., accuracy) affects metacognitive outcomes (Fleming & Lau, 2014), our final assessment of metacognitive performance is designed to account for possible differences in accuracy across our experimental factors by taking advantage of the range of stimulus values that were presented. That is, we wanted to compare whether confidence was the same for perturbations at the start, middle and end over trials when the accuracy was the same. To accomplish this, we took the accuracy data from each participants' performance on trials from a specific difficulty at a specific location (collapsing across the side of perturbation, for example, see filled circles in Figure 3A). Then, we looked for regions where their accuracy across these bins would overlap between their performance on trials for the three locations. To be clear, this meant that if a person had high accuracy in general for one location-condition and low accuracy in general for another location-condition, their region of overlap might be small. But, even in this case of low overlap, it would indicate that there was at least some set of trials for which accuracy was the same, despite overall performance differences, allowing a truer test of "second-order" metacognition independent of the "first-order" discrimination accuracy. These regions of overlap averaged 22.4% (SD = 8.3%) ranging from 56.1% to 78.5% accuracy (for data from a sample participant, see Figure 3). To quantify confidence across these areas of equal / overlapping accuracy, we then plotted each individual's confidence over their overlapping region and constructed polygons connecting their confidence over this region with a minimum value of 0. Finally, we took the area of these polygons (equivalent to the area underneath the connected-line curve of the plot of confidence against accuracy over the overlapping range) as the dependent measure for this final analysis. This measure of polygon-area was then entered into a one-factor 3-level RMANOVA across location (start, middle, and end, see Figure 3B for the mean polygons across all participants).

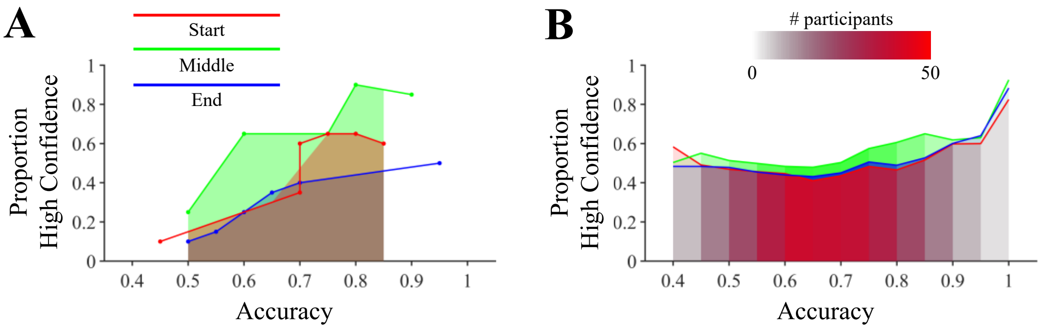

Figure 3. Average accuracy and proportion high confidence for each perturbation location. The colours red, green, and blue represent data from when the perturbation was at the start, middle, and end of the movement, respectively. (A) Data for one individual participant. (B) Average data

across 47 participants. The colour gradation corresponds to the number of participants contributing to each region of overlapping accuracy.

To account for the fact that we are running many multi-factorial RMANOVAs with multiple F-tests (main effects and 2- and 3-way interactions) we set the *p* value for all F-tests conducted in this study at 0.01. When conducting post-hoc comparisons between levels of a significant factor we used a Bonferroni corrected p-value of 0.05. Where Mauchly's test of sphericity was violated in the RMANOVAs, the Greenhouse–Geisser correction was applied to adjust the degrees of freedom.

3. Results

3.1 Accuracy and Confidence

For accuracy (see Figure 4), the RMANOVA yielded a main effect for location ($F(2, 98 = 13.16)$, $p < 0.01$, $\eta^2_p = 0.21$). Bonferroni corrected post-hoc comparisons between locations revealed that accuracy was significantly lower at the start (M = 0.64, SE = 0.017) compared to the middle (M = 0.71, SE = 0.014) and the end (M = 0.70, SE = 0.014), but accuracy did not differ significantly between the middle and the end (see Figure 4A). This finding shows that participants had better awareness of their limb position at the middle and end of their reach compared to the start. The RMANOVA also indicated a main effect for perturbation-amount ($F(5, 245) = 170.60$), $p = < 0.01$, $\eta^2_p = 0.78$). All corrected pairwise comparisons were significant except for the accuracy comparison between 60 and 80 pixels. This confirms that the perturbation levels selected for this task were effectively manipulating participants' accuracy, where increasing the size of the perturbation increased accuracy accordingly (see Figure 4B). However, participants' overall accuracy in the task was, in our estimation, quite low. Despite the significant visual deviation presented in the easiest condition (i.e., 120 pixels or 6.8 cm of perturbation), participants were still not reaching ceiling performance and had a maximum average accuracy of 82% (see Figure 4B). The main effect of side also reached significance (*F*(1, 49) = 9.11, $p < 0.01$, $\eta^2_p = 0.16$), suggesting that participants' accuracy was higher on trials in which the trajectory was perturbed to the right (M = 0.73, SE = 0.015) than those in which the trajectory was perturbed to the left (M = 0.64, SE = 0.022). The RMANOVA of accuracy did not yield any significant interactions.

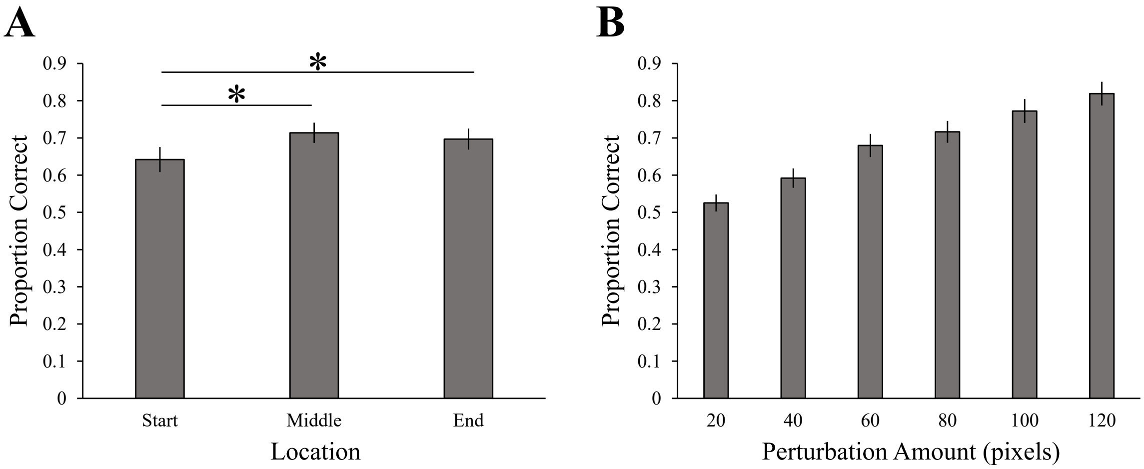

Figure 4. (A) Accuracy across the 3 locations of perturbation. Asterisks between the bars represent a significant difference between conditions. (B) Accuracy across all perturbation amounts. All contrasts were significant except for the contrast between 60 and 80. For both A and B, error bars represent 95% within-subject confidence intervals.

For confidence (see Figure 5), the main effect of location reached significance (*F*(1.7, 98) = 21.16), $p < 0.01$, $\eta^2_p = 0.30$). Bonferroni corrected post-hoc comparisons showed that confidence ratings were significantly different between all pairs of locations (see Figure 5A). More specifically, participants were the least confident at the start (M = 2.91, SE = 0.061) more confident in the end (M = 3.02, SE = 0.061), and the most confident in the middle (M = 3.15, SE

= 0.061). This pattern of discrepancy between the results from Accuracy, where performance at the End and Middle were not statistically different and these results from Confidence, where judgements at the End and Middle do differ is a first suggestion that there may be metacognitive factors at play. That is, discrimination performance is not tracking one-to-one with confidence. The RMANOVA also revealed a main effect for amount (*F*(3.17, 245)= 57.79), $p < 0.01$, $\eta^2_p =$ 0.54) with all but one (100 vs 120) corrected post-hoc contrast reaching significance (see Figure 5B). The main effect of side was not significant (*F*(1, 49) = 0.44), $p = 0.51$, , $\eta^2_p = 0.009$), suggesting that participants' confidence did not differ between trials in which the trajectory was perturbed to the right and those in which the trajectory was perturbed to the left. The RMANOVA for confidence also did not yield any significant interactions.

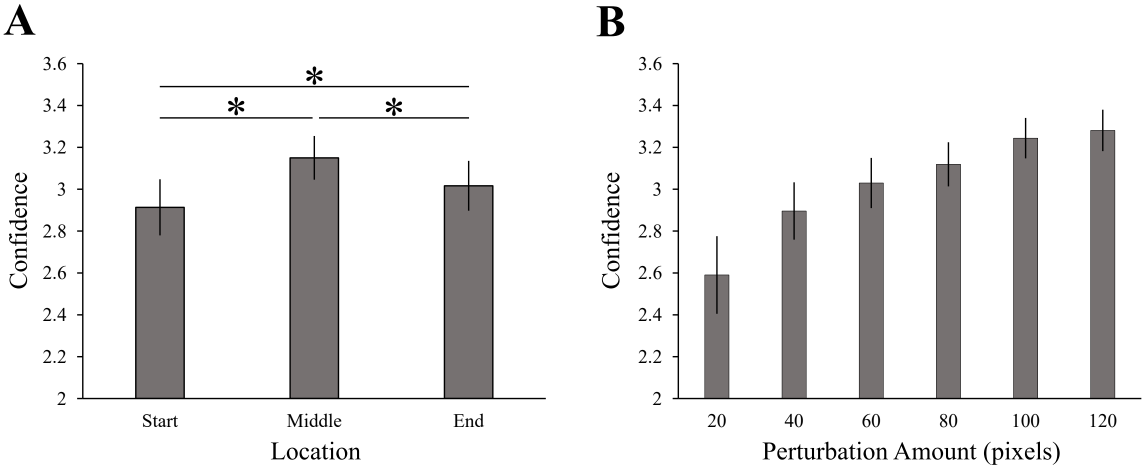

Figure 5. (A) Confidence levels across the 3 locations of perturbation. Asterisks between the bars represent a significant difference between conditions. (B) Confidence levels across all perturbation amounts. All contrasts were significant except for the contrast between 100 and 120. For both A and B, error bars represent 95% within-subject confidence intervals.

3.2 Metacognition Analysis

Our first analysis of metacognition looked at confidence on correct versus incorrect trials (see Figure 6). This RMANOVA revealed a main effect of location (*F*(1.74, 98) = 16.22), $p < 0.01$, $\eta^2_p = 0.25$) a main effect of accuracy (*F*(1, 49) = 70.43), $p < 0.01$, $\eta^2_p = 0.59$) and a location x accuracy interaction (*F*(2, 98) = 6.39), $p < 0.01$, $\eta^2_p = 0.12$). The location effect repeats the previously reported location effects on confidence with significantly higher confidence at the middle compared to the start and end. The accuracy effect provided evidence that participants in this experiment were showing metacognitive sensitivity as they were more confident on correct trials (M = 3.11) than on incorrect trials (M = 2.73). Finally, the location x accuracy interaction is intriguing, as it suggests that metacognitive sensitivity (the degree to which confidence follows accuracy) is not the same at each location. The follow up Bonferroni corrected comparisons of the correct-incorrect difference across the levels of location showed that the correct-incorrect difference was significantly larger at the middle location (M= 0.44, SE = 0.057) than at the start (M = 0.29, SE = 0.041), with the end location having a difference somewhere in between (M = 0.40, SE = 0.054) (see Figure 6). However, as previously noted, this analysis may introduce performance confounds into the confidence data by collapsing across perturbation-size; if the relationship between task performance and perturbation-size differs across any of the RMANOVA factors, these differences in task performance could influence the corresponding confidence data (Fleming & Lau 2014), making it unclear if the RMANOVA effects on confidence reflect direct influences on metacognitive processes, or only reflect an indirect influence through the mediating factor of task performance. To account for this ambiguity, we turn to our second analysis in which task performance is precisely controlled across experimental factors and so it cannot pose an analysis confound.

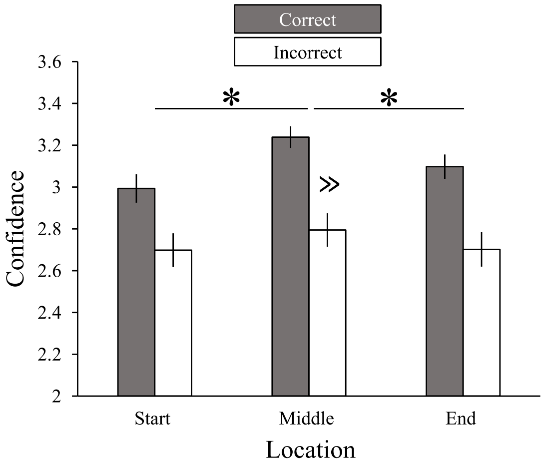

Figure 6. Confidence levels for correct and incorrect trials across the 3 locations of perturbation. Asterisks between the bars represent a significant difference between conditions. The double greater than symbol (>>) represents the result of the location x accuracy interaction, which shows that the correct-incorrect difference is greatest at the middle location. Error bars represent 95% within-subject confidence intervals.

In this second analysis, we compared the area of the polygon (or, under the curve) of accuracy versus confidence plots over regions of overlapping accuracy across the three perturbation locations (see Figure 3 for Method and Figure 7 for Result). 3 participants were removed from this metacognition analysis due to having no regions of overlap across their 3 location conditions, leaving 47 participants. The one-factor RMANOVA comparing these equal-accuracy confidence areas across locations revealed a significant effect ($F(1.72, 92) = 7.79$), $p < 0.01$, $\eta^2_p = 0.15$). Bonferroni corrected post-hoc comparisons show that these areas were significantly larger at the middle location (M = 0.120, SE = 0.0094) compared to both the start (M = 0.104, SE = 0.0088) and end (M = 0.107, SE = 0.0091) locations, while being statistically similar between the start and end (see Figure 7). This result is the most compelling evidence we provide that there are differences in metacognition between different stages of a movement. Because accuracy is held constant, the higher average confidence observed at the middle cannot be attributed to differences in task performance, but rather it reflects a difference in metacognitive processes.

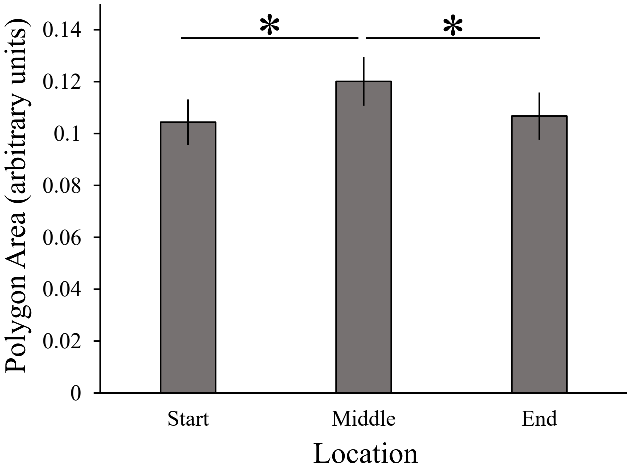

Figure 7. Average area under the curve (AUC) of accuracy versus confidence plots over regions of overlapping accuracy across the three perturbation locations. Asterisks between the bars represent a significant difference between conditions. Error bars represent 95% within-subject confidence intervals.

4. Discussion

In the introduction, we described an apparent paradox in people's awareness of their movements. On the one hand, research on the visual control of action (e.g., Goodale et al., 1986; Fourneret & Jeannerod, 1998) suggests we have almost no ability to consciously report details of our movement, but can still execute movements with remarkable accuracy and even adapt our reach to account for perturbations we don't notice. On the other hand, research on the metacognition of action (e.g., Arbuzova et al., 2021) shows that we actually do have some access to information about our movements, because we can successfully monitor decisions based on our movement details. We argued that considering the stage of movement being investigated could help to explain this paradox, based on previous research suggesting that limb position awareness and the availability of attentional resources may differ across stages of a reach (Tremblay et al., 2017; de Brouwer et al., 2018; Posner & Keele, 1969; Khan et al., 2006). Thus, the present study investigated individuals' awareness of their hand moving through space when making a reach and whether this awareness differed at the start, middle, and end of a goal-directed reaching movement. We also explored participants' capacity to metacognitively monitor their movements, and whether metacognitive processes also changed between different movement stages. To accomplish this, participants made judgements on a reach they had just completed to identify their own movement trajectory from a deviated one, followed by rating their confidence in their decision. To isolate different stages of the reach, a perturbation was either presented at the start, middle, or end of the trajectory. We made three predictions at the start of this study. First, we anticipated that participants' overall ability to discriminate between their own trajectory and a deviated one would be poor. We indeed found that overall accuracy in the task was relatively low, as participants were unable to achieve ceiling performance even in the easiest condition (i.e., despite a significant visual deviation). This result suggests that in general, humans have poor awareness of their arm position when they move. Second, we predicted that when looking at awareness between different movement stages (start, middle, or end), accuracy would be higher when the visual deviation was presented at the start and end of the movement trajectory. Our results differed from this prediction in that we found that accuracy was higher when the deviation was imposed at the middle and end of the movement compared to the start, indicating that awareness of limb position is further reduced at the start of a movement. Our final prediction was that individuals would possess some ability to metacognitively monitor their reaches (i.e., that their confidence would track their accuracy), but that metacognitive monitoring at different locations would follow that of accuracy and be heightened at the start and end of a movement. Our findings confirmed that participants had some ability to metacognitively monitor their movements because overall, they provided higher confidence ratings when they were correct and lower confidence ratings when they were incorrect. We also found that after controlling for accuracy, participants showed more confidence when the deviation was in the middle of their reach. Though we initially hypothesized that participants' ability to metacognitively monitor their movements would be greater at the start and end, we cannot conclude that these processes are necessarily "enhanced" in the middle because our analysis involved average confidence rather than differences in confidence between correct and incorrect trials.

Our overall finding that accuracy in the task was poor corroborates evidence of low awareness of limb position during upper-limb movements. Based on previous work (Fourneret and Jeanerod, 1998; Goodale et al., 1986; Pélisson et al., 1986; Prablanc & Martin, 1992), details of an individual's motor performance are poorly accessible to conscious awareness and some processes governing motor control are distinct from those that generate conscious judgement. Additional research has shown that while individuals might be unaware of a target shift, this unawareness is dissociated from motor awareness of the visuomotor adjustment to that shift. This suggests that motor awareness and perceptual awareness are independent processes in the brain, with different neural substrates and natural time courses (Johnson & Haggard, 2005). Moreover, Johnson et al. (2002) propose that visuomotor corrections can enter conscious awareness under certain conditions. The key factor is whether the visuomotor correction matches the intended movement. In other words, individuals may turn on a supervisory system to monitor their actions only when monitoring is necessary to achieve the goal of the task (i.e., when the stimulus and response are counterintuitively related, see Johnson et al., 2002). Nevertheless, under normal conditions, humans have limited awareness of their movement details.

Our second hypothesis that participants would demonstrate better awareness of their limb position at the start and the end of the trajectory was not supported by the results. Instead, we found that accuracy was lowest when the deviation was imposed at the start of the movement compared to the middle and end. Reduced performance at the start of a movement could be attributed to limited attention at this stage where only a portion of the information can be processed when briefly confronted with several visual stimuli in a display due to the limited capacities of the visual system. As a result, visual attention enables the selection of the currently most relevant information to effectively guide our behaviour (Carrasco, 2011). To explore attentional demands of arm movements at different stages, Posner and Keele (1969) had participants perform a tracking task (i.e., primary task) while responding to the presence of an auditory tone (i.e., secondary/ probe task). The purpose of the secondary task was to assess how much attention was available for performing a second task alongside a primary task. The authors found that reaction time to the tone was greatest when it was presented at the start of the movement compared to the middle and the end. Such a result implies that relative attentional demands change throughout different stages of a movement, with more attentional resources being used at the start. In a similar experiment done by Khan et al. in 2006, probes were presented at different positions of a movement to assess the processing demands associated with both programming and online regulation. That is, probes could be presented during the reaction time interval of the movement (i.e., to assess programming) or at several points after the initiation of the movement (i.e., to assess online regulation). The results showed that probe RT was greatest during the reaction time interval of the movement, implying that movement programing processes, which demand attentional resources, are taking place during this period. In terms of online regulation, probe RT was highest when the movement was initiated and then decreased as the movement continued, suggesting that the system is busiest at the start and then resources become more available as the movement progresses.

However, the results of the current study suggest that whatever attentional resources are being allocated to the start of a movement do not help in estimating the position of the limbs in space, but may instead be directed towards movement planning. Indeed, the premotor theory proposes that spatial attention results from the activation of the motor system and shifts of attention occur through the planning of goal-directed actions such as reaches (see Rizzolati et al., 1987). This theory suggests that the neural substrates used for selective attention and movement planning overlap, indicating that the system controlling action is the same system that also controls spatial attention. Despite earlier work focusing on the connection between selective attention and the preparation of eye movements, the premotor theory extends beyond the attentional preparation of oculomotor responses. Instead, it proposes a broader relationship between visual attention and any form of motor preparation (Rizzolati et al., 1994). For instance, attentional orienting processes are elicited during unimanual response preparation (Eimer et al., 2005). The premotor theory would suggest that the attentional limitations before and during the initiation of a movement, observed in Posner and Keele (1969), Khan et al. (2006), and the present study, are a consequence of movement planning. Alternatively, some theories propose that rather than being the same system, attention and movement planning share a single common visual attention mechanism (i.e., visual attention model, see Schneider, 1995). Nevertheless, both theories imply that visual attention and movement planning are highly connected and that when a movement is initiated, attention is preferentially used for movement planning rather than other functions.

Further support for the interplay of attention and planning stems from neurophysiological research demonstrating that visual attention and visual guidance share common neural structures. Areas within the posterior parietal cortex (PPC) are activated during the preparation of saccadic eye movements, prior to reaching movements, and during visually guided grasping, highlighting their role in the preparation of visually guided movements (Balauf & Deubel., 2010). The PPC also plays a significant role in shifting spatial attention, as shown by its activation during attentional tasks (Shikata et al., 2003) and its function in mediating the connection between spatial attention and movement planning (Balauf & Deubel, 2010).

Interestingly, the PPC may also play a role in multisensory limb position representation (Limanowski & Blankenburg, 2016), given the wealth of evidence suggesting that activity in the PPC represents both the seen and felt position of the hand (Graziano et al., 2000). Neurophysiological investigations in the past have shown that areas within the PPC receive input from both visual and somatosensory areas and may also receive an efference copy of arm movement commands (Andersen et al., 1990; Rushworth et al., 1997), indicating their role in limb position estimation. Additionally, the PPC is involved with comparing visually derived signals from target positions with limb position signals from somatic sources (Shi et al., 2013), and plays a critical role in generating and guiding spatial awareness, as well as one's sense of orientation and limb location (Whitlock et al., 2017). Hence, given that limb position estimation may be another role carried out by the PPC alongside movement planning and directing spatial attention, this provides compelling evidence that fewer resources are available to estimate body position at the start of a movement when movement planning is occurring.

While this theory offers insight into why participants in the current study exhibited low awareness of their limb position at the beginning of a movement, it does not explain *where* attention goes at this stage. Several studies have described a spatial gradient in attentional allocation, with more visual resources directed to positions that are more important from a motor planning point of view (Baldauf et al., 2008; Baldauf & Deubel, 2008; Baldauf et al., 2006). For instance, during movement planning, attention may be directed towards sources of task-relevant information about action outcomes, such as the reach target. Indeed, Baldauf and Deubel (2010) suggest that during the preparation of hand movements, attention is being directed towards the intended movement goal. Visual information at this source is useful for action selection purposes and for providing feedback about movement outcomes (Mahon et al., 2020). Keller et al., (2005) also suggest that attention is allocated to strategically monitor movement outcomes, as participants who direct attention to monitor their movement outcomes tend to perform better than those who attend to the movement itself. To investigate attention allocation during goal-directed movements, Baldauf et al., (2006) and Baldauf and Deubel, (2008) presented discrimination targets at different spatial locations while participants were performing a reach. The authors found enhanced sensitivity for stimuli presented at the targets of upcoming actions compared to locations that were not relevant for the movement. Notably, discrimination targets were presented before movement initiation (i.e., during movement planning), suggesting that when preparing for a reaching movement, attention is already being directed towards monitoring the outcome of the intended action. Further support for the deployment of attention towards the reach target during planning comes from Gielen et al. in 1985, who observed that acceleration at movement onset is greater when reaching towards distant targets compared to closer targets. There is also evidence that the initial direction of the hand at movement onset aligns closely with the direction of the target (e.g., Messier & Kalaska, 1999). Additionally, if we consider Polit and Bizzi's work from 1978, perturbations to a limb at the start of a movement do not appear to hinder movement planning as central commands must be able to control final arm position independently of initial position. In their experiment, monkeys were trained in a task where they pointed to one of ten lights that illuminated, without visual feedback of the arm. On some trials, a load was applied to the monkey's arm to cause unexpected changes in the initial arm position. The monkeys then underwent a deafferentation procedure and performed the same task. The authors found that both intact and deafferented monkeys always reached the final intended arm position, even when the load resulted in a change in the initial position of the arm. Notably, the deafferented animal did not have sensation in their arm, so they could not feel the displacement of the applied load. This suggests that visually evoked arm movements depend on a process that specifies final position, as changes in the start position or even loads applied to a limb do not prevent the CNS to plan for a final limb position. Taken together, these results indicate that arm movement planning is largely based on extrinsic properties of the target. Returning to the present study, it is possible that attention is directed towards the reach target at the beginning stages of a movement and then becomes available for estimation of body position after movement planning has terminated (i.e., by the middle and end of a reach).

To summarize, it is well-established that attention is constrained due to the limited capacities of the PPC, leading to the prioritization of certain processes over others. The PPC serves various functions including spatial attention (Shikata et al., 2003), movement planning (Baldauf & Deubel, 2010), and limb position estimation (Limanowski & Blankenburg, 2016). At movement onset, it seems likely that PPC activity is primarily devoted to movement planning (e.g., Baldauf and Deubel, 2008), allowing for the selection and specification of appropriate motor commands to achieve a goal, such as accurately reaching towards a target. Indeed, previous work by Posner & Keele (1969) and Khan et al. (2006) suggests that attention is limited before and during the initiation of a reach, and other research has suggested that attention and movement planning are highly connected (Rizzolati et al., 1987). Therefore, we propose that participants in the present study may have shown lower accuracy when identifying their movement from a deviated one at the start location because attention was likely focused on movement planning processes rather than monitoring the moving limb. When movement planning concluded, PPC activity became available for limb position estimation. Consequently, participants showed greater accuracy in identifying their trajectory from a deviated one during the middle and end stages of their reach.

So far we found that awareness of limb position is low, particularly at the start of a movement, likely due to attentional limitations associated with movement planning. However, individuals can make accurate reaches without being aware of the details of their moving limb because visually guided movements are controlled by the dorsal stream of vision which operates outside of conscious awareness. The classical work of Goodale & Milner (1992) suggests that we should be able to control a movement accurately using visual guidance (i.e., dorsal stream, unconscious) but that this information should not be available for conscious report (i.e., ventral stream, conscious). While some research has proposed that the dorsal and ventral streams are controlled by distinct attentional mechanisms (e.g., Enns & Liu, 2009), this does not fully explain the results of our investigation. In our study, participants exhibited low accuracy overall, yet their confidence ratings scaled with their accuracy, indicating that they were aware of their uncertainty regarding their limb position. Hence, participants still had access to some information about the decisions based on their movement details. This may be a case when the distinction between the dorsal and ventral stream of vision is weak, given the well-documented interactions between both streams. Indeed, perceptual and visuomotor processing share common processing and attentional resources (Kunde et al., 2007, Hesse & Deubel, 2011; Hesse et al., 2012; Mahon et al., 2007). Further, tool use is a special case of visuomotor behaviour where a complex interaction between the dorsal and ventral stream takes place. For instance, Valyear & Culham (2010) showed that when using tools, the ventral stream provides information about how the object should be engaged, which contradicts the idea that visually guided actions are carried out independently and in the absence of conscious object perception and recognition. However, even more relevant to the current study is the idea that dorsal stream processing can contribute to conscious experience (Madary, 2016), as information originating from the dorsal stream can influence object recognition (Almeida et al., 2008; Helbig et al., 2006; and Mahon et al., 2020). Support for this concept also comes from studying patient DF, who has damage to her ventral stream. She has been extensively studied in the context of the two visual streams hypothesis due to her difficulty in perceiving object shape and orientation, despite being able to use these visual features to guide her actions. While DF's behaviour has traditionally been cited as evidence for distinct processes governing perception and action, Schenk (2006) found that she can actually describe certain visual features that guide her actions, suggesting that her brain can access some "unconscious" information used by the dorsal stream.

A metacognition study by Pereira et al. (2023) also demonstrates that participants had access to unconscious information from the dorsal stream. The authors showed that visuomotor signals were used to guide confidence ratings about the presence of a deviation even if participants were not perceptually aware of the deviation. The authors propose that participants had access to at least a summary of visuomotor cues that guided their explicit detection and confidence responses, allowing them to consciously monitor their ongoing movements. Their findings also challenge the idea that minor deviations are mostly corrected without conscious awareness. Instead, they suggest that individuals may be unconscious of certain corrections while still possessing a calibrated “feel” of their performance. Likewise, the current study revealed that individuals may lack awareness of specific movement details while still retaining a sense of their overall performance, as shown by their confidence ratings.

A possible mechanism to explain how we process information that we may not even consciously perceive is proposed by Pereira et al. (2022). It is well established that stimulus detectability involves the accumulation of sampled evidence towards a decision bound (Kang et al., 2017). As such, a stimulus is consciously perceived when an unconscious evidence accumulation process reaches a threshold (Moutard et al., 2015). In terms of confidence ratings, Pereira et al., (2022) suggest that perceived confidence scales with the distance between the maximum amount of accumulated evidence and the detection threshold. Critically, because this distance can be defined even if the threshold is not crossed, this explains why confidence can accurately reflect the accuracy of decisions regarding stimuli that are unseen or unconscious, as observed in both our study and Pereira et al.’s (2023) study. It is also worth mentioning that the mechanism of evidence accumulation governing subjective reports of perceptual consciousness and monitoring is regulated by the PPC (Pereira et al., 2022), a region we previously discussed as being implicated in movement planning, attention, and limb position representation.

With respect to motor metacognition, we found that when controlling for accuracy, confidence was highest in the middle of the reach, which also contrasts with our original hypothesis. We had anticipated that metacognitive processes would follow the same pattern of awareness and be enhanced at the start and end. However, because we are looking at average confidence, we cannot conclude what exactly is driving the increased confidence in the middle. To accomplish this, a signal detection theory (SDT) approach is required, which involves determining how well an observer can discriminate between their own correct and incorrect responses using their confidence ratings (Maniscalco & Lau, 2012). This concept is also known as metacognitive sensitivity. Another measure used in SDT analysis is metacognitive bias which is a difference in subjective confidence despite basic task performance remaining constant (Fleming & Lau, 2014). In the current study, we were not able to perform an SDT analysis as it requires higher trial counts, and therefore cannot determine if the increased confidence in the middle is a result of metacognitive sensitivity, metacognitive bias, or both. While we have established a real difference in terms of metacognitive processes in the middle stage, future work should use SDT analyses to determine the relative contributions of sensitivity and bias to the result seen in the current study.

It is also worth noting that we observed a significant effect of the side that the deviation was presented on relative to the original trajectory. Participants were more accurate in identifying their own movement when the trajectory was perturbed to the right side of the original compared to the left side. It is possible that participants were biased towards choosing the trajectory presented on the right, contributing to the observed increase in accuracy. Indeed, previous research has shown evidence of various rightward biases in reaching behavior. For instance, Gallivan and Chapman (2014) observed that right-handed participants are biased towards targets on the right side of space. Additionally, Johnson and Haggard (2005) noticed a rightward bias when participants reached towards a target that could jump to the right or the left side of space. Endpoints to rightward target shifts were deviated significantly towards the right of center compared to endpoints to leftward target shifts. Further, attention seems to be biased to the right side of space in right-handers during bimanual reaching (Buckingham & Carey, 2009). Taken together, these results could explain why in the current study, individuals are more likely to perceive their limb trajectory as more towards the right side of space than how they actually moved.

Lastly, as previously discussed, several pathological conditions including Parkinson's disease, Huntington's disease, and limb apraxia demonstrate impairments in motor awareness (Aaylward et al., 1997; Say et al., 2011; Spinelli et al., 2022). Therefore, an avenue for future research would be to explore how participants diagnosed with such disorders perform in awareness/metacognition tasks. This has previously been done by Verrel et al. (2023), who found that compared to normal subjects, patients with functional movement disorder (FMD) showed confidence ratings that were less predictive of the correctness of their decisions in a metacognitive reach task. However, investigating awareness and metacognition by location, as done in the current task, may give more insight into the specific mechanisms that are impaired in individuals with these conditions. Finally, future research should extend this work by having participants perform the same task in virtual or augmented reality. Although in the present study we explored awareness and metacognition while performing naturalistic reaching movements, participants were judging a 2D representation of their 3D reach. Conducting this task in VR/AR will allow participants to be in more realistic environments, and a more accurate assessment of awareness and metacognition can be achieved.

5. Conclusion

In the current study, we showed that healthy participants have limited awareness of their limb position during goal-directed movements, likely due to a disconnect between mechanisms governing motor control and those that generate conscious judgement. In addition, we provided novel evidence indicating differences in awareness and metacognitive monitoring of limb position at various stages of a movement. Participants had the most difficulty in discriminating between their own movement trajectory and a deviated one when a perturbation was presented at the start of a movement, indicating that attention may have been allocated towards other functions at this stage (i.e., movement planning) instead of limb position estimation. With respect to overall metacognition, participants' confidence ratings scaled with their accuracy despite showing low accuracy overall. Such a result suggests that even though some visuomotor information was not enough to discriminate between trajectories, it could still be harnessed to rate confidence. Finally, when accuracy was equated, average confidence levels were highest when the deviation was presented in the middle of the reach. Future research should extend this work to determine whether metacognitive sensitivity, bias, or both is driving the observed increase in confidence at this stage. Further avenues for future research also include conducting this task using patients with disorders of awareness/metacognition, and performing this task in VR/AR.

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