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EXPRESS: Hands of Confidence: When Gestures Increase Confidence in Spatial Problem Solving

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Hands of Confidence: When Gestures Increase Confidence in Spatial Problem Solving

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Abstract

This study examined whether the metacognitive system monitors the potential positive effects of gestures on spatial thinking. Participants ($N = 59$, 31F, $M_{age} = 21.67$) performed a mental rotation task, consisting of twenty-four problems varying in difficulty, and they evaluated their confidence in their answers to problems in either gesture or control conditions. The results revealed that performance and confidence were higher in the gesture condition, in which the participants were asked to use their gestures during problem-solving, compared to the control condition, extending the literature by evidencing gestures` role in metacognition. Yet, the effect was only evident for females, who already performed worse than males, and when the problems were difficult. Encouraging gestures adversely affected performance and confidence in males. Such results suggest that gestures selectively influence cognition and metacognition and highlight the importance of task- (i.e., difficulty) and individual-related variables (i.e., sex) in elucidating the links between gestures, confidence, and spatial thinking.

Keywords: confidence, representational gestures, mental rotation, metacognition, spatial thinking

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Hands of Confidence: When Gestures Increase Confidence in Spatial Problem-Solving

Classically defined as “cognition about cognition” (Flavell & Ross, 1981), metacognition is the ability to monitor and control one’s cognitive process across contexts and time points (e.g., Allen & Armour-Thomas, 1991; Dai et al., 2018), facilitating adaptive behavior in goal-directed ways (e.g., van der Plas et al., 2022). It supports future perceptual decisions (Boldt et al., 2019), conscious awareness (Koriat, 1993), social interactions (e.g., Bahrami et al., 2010; Frith, 2012; Shea et al., 2014), and a broad range of cognitive processes such as decision-making (e.g., Yeung & Summerfield, 2012; Pleskac & Busemeyer, 2010), learning (e.g., Guggenmos et al., 2016), attention (e.g., Rummel & Meiser, 2013), and cognitive control (e.g., Fernandez-Duque et al., 2000). Metacognition pervades many aspects of experience, and as such, the ways in which it supports various cognitive processes are under constant scientific exploration. This study examined the relationship between metacognition and gesture use during spatial thinking in adults. We specifically asked whether the metacognitive system monitors gestures’ potential effects on the mental rotation aspect of spatial thinking.

We particularly focused on spatial thinking for two reasons. First, attempts at explaining how people metacognitively monitor spatial thinking are scarce at best (e.g., Ariel & Moffat, 2018; Desme et al., 2019; Thomas et al., 2012); therefore, identifying the mechanisms underlying spatial processing has a theoretical value. Second, many studies found that spontaneous and encouraged uses of gestures enhance spatial processes (e.g., in adults; Chu & Kita, 2008, 2011, 2016; Göksun et al., 2013; in children, Ehrlich et al., 2006; Ping et al., 2011; Wakefield et al., 2019), thus making spatial tasks suitable for exploring how gestures and metacognition interact. Gestures’ effects on spatial thinking are mainly explained in terms of their role in the gesturers' thoughts (e.g., Goldin-Meadow & Beilock, 2010; Goldin-Meadow et al., 2009; Kita et al., 2017). However, the ways in which gestures

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interact with the metacognitive system, responsible for monitoring and controlling the cognitive processes under such change, have never been previously investigated. Here we asked if encouraging adults to use gestures during spatial problem-solving would positively influence their performance and metacognitive monitoring of such influence (i.e., performance confidence) for the first time in the literature.

Metacognitive Monitoring of Spatial Thinking

As a multi-layered construct, spatial thinking comprises mental operations involved in encoding, visualizing, manipulating, retrieving, and reasoning about tools, objects, places, and dynamic spatial displays (e.g., Ariel & Moffat, 2018; Hegarty, 2010; Newcombe, 2010; Uttal & Cohen, 2012; Xie et al., 2018). Many everyday tasks that require individuals to mentally orient themselves or objects in space, such as packing a suitcase or navigating familiar and unfamiliar places, are part of spatial thinking processes (Charcharos et al., 2016). Efficiency in spatial thinking is also closely related to better learning and reasoning outcomes in science, technology, engineering, and mathematics (STEM) areas (e.g., Newcombe, 2016; Wai et al., 2009; Uttal & Cohen, 2012), and it predicts attainment in work settings requiring excellent spatial skills (e.g., Wai et al., 2009; Uttal & Cohen, 2012).

Metacognitive processes monitor spatial thinking and regulate the implementation of compensatory acts toward increasing processing efficiency. Experimentally, the monitoring aspect of metacognition is assessed in the form of confidence judgments. Confidence judgments are explicit judgments about performance, presumably reflecting individuals' thoughts about the degree of learning, the demands of cognitive processing (e.g., task difficulty), or the accuracy of task performance (e.g., Cooke-Simpson & Voyer, 2007). Metacognitive monitoring is a heuristic process (Dunlosky & Tauber, 2014) during which theory-based or experience-based cues are considered (e.g., Koriat, 1997; Koriat & Levy-Sadot, 1999; Nelson, 1996). Theory-based cues are individuals' naïve beliefs or perceptions

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about their abilities (e.g., self-efficacy, Bandura, 1971; attitudes, Sidney et al., 2021). Experience-based cues are about the information derived from internal signals during a performance (e.g., Boldt et al., 2017; Fleming & Daw, 2017), such as the fluency with which the information is processed, accessibility, familiarity, and relatedness of the target information (e.g., Baranski & Petrusic, 1998; Koriat, 1997; Nelson & Narens, 1990). The Dynamic Signal Detection Theory (Pleskac & Busemeyer, 2010) assumes confidence judgments result from evidence accumulation. Individuals compute the probability of a correct decision explicitly or implicitly during post-decisional processes integrating multiple cues (i.e., perceptual and mnemonic strength, familiarity with the decision, and priors such as the experience of success/failure) and end up with a confidence judgment (e.g., Boldt et al., 2019; Fleming & Daw, 2017; Koriat & Goldsmith, 1996; Navajas et al., 2016; Rhodes & Castel, 2008).

Despite its importance, metacognitive monitoring of spatial thinking has been the main interest of very few studies, which primarily focus on age (e.g., Ariel & Moffat, 2018; Thomas et al., 2012) or sex differences (e.g., Ariel et al., 2018; Cooke-Simpson & Voyer, 2007; Desme et al., 2019; Estes & Felker, 2012). The results of these studies favor males over females in terms of performance and confidence and highlight confidence as a predictor of performance differences between sexes. The results on age differences are inconclusive in terms of confidence, with Thomas et al. (2012) suggesting increasing difficulties in monitoring spatial performance with age and Ariel and Moffat (2018) indicating intact monitoring ability spared from age-related declines in performance. All in all, the limited number of studies on monitoring spatial ability focus on group comparisons and different aspects of spatial thinking (e.g., self-perceptions of spatial ability and spatial visualization in Ariel & Moffat, 2018; mental rotation in Cooke-Simpson et al., 2007 and Estes & Felker, 2012; visual-spatial working-memory in Thomas et al., 2012).

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No previous study defined the cues people use to infer the quality of their spatial thinking. To date, studies have primarily focused on the cues people use to monitor episodic or semantic memory processes (e.g., Benjamin et al., 1998; Rhodes & Castel, 2008) or perceptual/sensory decisions (e.g., Kvidera & Koutstall, 2008). On the other hand, as summarized above, studies on metacognitive monitoring of spatial thinking focused on the age and sex differences and not inquire into the cues utilized during metacognitive monitoring (i.e., Ariel et al., 2018; Ariel & Moffat, 2018). Therefore, with the current empirical evidence, it is hard to explain whether monitoring spatial thinking is also a cue-driven heuristic process. It is unclear whether people attend to different cues across different spatial tasks or similar cues that differ in their informativeness during spatial performance monitoring (Ariel & Moffat, 2018; Dunlosky & Tauber, 2014). However, although the exact ways of monitoring spatial performance have not been clearly described, the findings compellingly suggest that people use fluency cues for generating and manipulating visuospatial representations and the perceived vividness of these representations as cues in determining their confidence in spatial tasks (e.g., Ariel & Moffat, 2018).

Gestures and Spatial Thinking

Gestures are hand movements that are used to represent and communicate information without directly changing the physical world and can be used to depict actions or objects (iconic gestures), reference a specific item, location, or trajectory (deictic gestures), or represent abstract ideas (metaphoric gestures) (e.g., McNeill, 1992; Kita et al., 2017). Gestures are frequently produced during spatial tasks because they are spatial in nature (McNeill, 1992). They externalize gesturers` thoughts about the problem at hand (e.g., Church & Goldin-Meadow, 1986), represent how people mentally visualize problems (e.g., Alibali et al., 1999), and give information about the spatial strategies used during problem-solving (e.g., Alibali et al., 2011). In this study, we specifically focused on iconic gestures

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because previous studies suggest that people mostly use iconic gestures during spatial tasks, and the frequency of iconic gestures increases when they solve and explain their solutions to complex spatial visualization problems (e.g., Brooks et al., 2018; Chu & Kita, 2008, 2011; Yang et al., 2020). Therefore, from now on, we will use the term gesture to refer specifically to iconic gestures.

Gestures support various spatial processes. They aid mental rotation (in adults; Chu & Kita, 2008, 2011, 2016; Göksun et al., 2013; in children, Ehrlich et al., 2006; Ping et al., 2011; Wakefield et al., 2019), spatial reasoning (e.g., Chu & Kita, 2011), tracking dynamic spatial displays (Macken & Ginns, 2014), and encoding spatial relations (Chong et al., 2013). In this study, we examined gestures' effects on the mental rotation aspect of spatial thinking and confidence, encouraging participants to use their gestures during spatial problem-solving. Previous studies have mainly focused on spontaneous gestures during mental rotation, and gesture use was manipulated mostly in child studies (i.e., Erhlich et al., 2006; Wakefield et al., 2019). These studies suggest that mental rotation skills are malleable and can be improved through encouraging gestures during spatial problem-solving. Gestures increase accuracy in mental rotation task performance, and their effect is even more pronounced than the effect of a real action experience in which the participants practice rotating the objects in question. In the only study conducted with adults, encouraging gestures, Chu and Kita (2011, Experiment 2) found that the gesture-encouraged group performed better than the gesture-allowed and gesture-prohibited groups in a mental rotation task. In all three groups, participants produced more gestures during difficult problems compared to the easy problems, suggesting that difficulty in spatial visualization triggers spontaneous and encouraged uses of gestures. Chu and Kita (2011) also found that the frequency of gestures declined over trials in the gesture-encouraged group, meaning that the participants became better at solving problems through the help of gestures during task performance. This result

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suggested that gestures do not only externalize spatial mental representations into hand movements. Instead, they actively help internalize the computation of spatial transformations during spatial visualization.

Gestures transform implicit knowledge into explicit by offloading immediate spatial representations (e.g., Broaders et al., 2007; Cartmill et al., 2012; Hostetter & Alibali, 2008). They also help build rich mental representations (Chu & Kita, 2011) and reduce the cognitive load of the gesturer (e.g., Goldin-Meadow & Wagner, 2005). The Gesture- for -Conceptualization hypothesis (Kita et al., 2017) forms a coherent framework for explaining gestures' self-directed functions on cognition. It suggests that gestures differ from propositional and verbal thinking; they are representational and do not directly change the physical world (Novack & Goldin-Meadow, 2016). This representational nature of gestures makes them more flexible and influential than actions. Gestures schematize information; they facilitate the encoding of spatial information more than actions (So et al., 2014) through four functions; activating, manipulating, packaging, and exploring spatial-motoric information for thinking and speaking.

What is essential to consider in interpreting research results is that gestures do not exert the same influence under different conditions and on different individuals (e.g., Kita & Özyürek, 2003; Özer & Göksun, 2020). An important external source of variation pertains to differences in the nature of the tasks. Gestures are helpful when perceptual-motor information is critical for problem-solving (i.e., in mental rotation, Chu & Kita, 2011) and when spatial processing is demanding but detrimental when external spatial tools are not needed (e.g., Alibali et al., 2011). There are also within-individual variations in response to gesture use, and recent studies highlight the importance of discussing the benefits of gestures considering the gesturer's cognitive skill set (for a review, Özer & Göksun, 2020). Research suggests that

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individuals with the most heavily taxed cognitive resources (i.e., low spatial ability and visual and spatial WM capacity) are the ones who gesture the most, showing that they may be using gestures as a compensatory tool (e.g., Chu et al., 2014; Gillespie et al., 2014; Göksun et al., 2013; Hostetter & Alibali, 2007; Smithson & Nicoladis, 2013). Recently Oviatt et al. (2021) suggested that expertise is also a within-individual variation that changes the way people gesture. Experts of a task know how to use their gestures in a way that would help them. They dynamically downshift their rate of gesturing on easy tasks and upshift it on harder ones that require cognitive effort. This line of evidence highlights the critical importance of establishing external and internal variations in gesture use to fully explain the mechanisms of self-directed influences of gestures on cognition.

In summary, current evidence implies that gestures change the content of the mind of gesturers' by activating and facilitating relevant mental simulations of physical movements and spatial positions (e.g., Chu & Kita, 2008, 2011; Goldin-Meadow & Beilock, 2010; Goldin-Meadow et al., 2009). The metacognitive system makes us monitor the content of our minds all the time, with or without conscious awareness, to determine future actions and behaviors (Shea et al., 2014). If gestures affect the content of the mind, they should also influence how the metacognitive system monitors the content, and this question has not been answered so far.

The Current Study

The current study examined how the metacognitive system monitors gestures' potential facilitatory effects on the mental rotation aspect of spatial thinking. We tested participants in gesture or control conditions in which they were encouraged to use gestures during problem-solving or not given any instructions, respectively. We used Chu and Kita (2011) 's mental rotation task, including twenty-four problems requiring participants to manipulate 3D Shepard and Metzler's (1971) type objects in their minds. Participants chose

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the rotated version of a particular object among the alternatives in each problem, which varied in difficulty and provided confidence judgments after each solution.

Gestures and metacognitive processes can interact dynamically and reciprocally in several ways during mental rotation. If gestures help maintain pre-existing spatial-motoric mental representations and activate new ones (Kita et al., 2017), they should increase the fluency with which information is processed. Relatedly, availability cues should be high when confidence in the stimuli learned using gestures is evaluated. Fluency and availability cues are the most evidenced cues on which people base their confidence. Here we speculate that gestures influence cognition by facilitating such metacognitive cues to an extent, attributing to metacognitive monitoring a mediatory role, especially in spatial tasks. Relatedly, we suggest that metacognitive confidence evaluations inform the cognitive system in turn and regulate the use of compensatory tools to increase performance (i.e., gesture use).

Based on such reasoning, we first hypothesized to observe higher mental rotation task performance in the gesture group than in the control group because of the encouraged use of gestures during problem-solving. Second, we expected that the effect of gestures on mental rotation task performance would be reflected in the confidence judgments made by the gesture group participants. We predicted that the gesture group participants would feel more confident about their decisions than the participants in the control group, further documenting gestures` effect on metacognition. Third, gestures were expected to be used purposefully by the participants. We hypothesized that participants would produce more gestures when they feel less confident (i.e., when the problems are more difficult than easy), in line with our argument that the metacognitive system would monitor the effects of gestures during spatial thinking and strategically regulate the uses of gestures.

Peripherally, we hypothesized that participants would show individual-related variations in the mental rotation task performance and confidence. We mainly expected sex

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differences in performance, favoring males, considering that a sex difference in mental rotation is the most documented difference between males and females in the literature (e.g., Estes & Felker, 2012; Hegarty & Waller, 1995; Hegarty, 2018; Linn & Petersen, 1985; Martens & Antonenko, 2012; Voyer et al., 1995). Relatedly, males and females were expected to differ in how gesture encouragement was used. Individuals differ in interacting with the environment (Uttal et al., 2013). Therefore, diverse ways of improving spatial thinking, such as the gesture encouragement strategy we employed in this study, may not operate the same for different populations that presumably differ at the baseline level (e.g., males and females; young and old adults, see for reviews Uttal et al., 2013; Özer & Göksun, 2021). Earlier research suggests that males and females use different strategies during mental rotation (i.e., holistic vs. dynamic, e.g., Goldstein et al., 1990; Hegarty et al., 2018), and males are generally more efficient at monitoring the efficiency of their strategy selection (e.g., Ariel et al., 2018; Hegarty et al., 2018). We predicted that encouraging gesture use can present, especially for females, a new strategy to solve mental rotation problems by changing the way they manipulate spatial-motoric information in their minds and providing various possibilities for what information to focus on (i.e., exploration function of gestures, Kita et al., 2017). Males are generally better at spatial tasks and confident in their spatial abilities; based on that, we expected to observe more pronounced effects of gestures on females' performance and confidence than we would see in males.

Method

Preregistration

Before data collection, the current study's main hypotheses, planned procedure and analyses were pre-registered via the Open Science Framework (OSF; http://osf.io/). We made a minor change in the procedure of the preregistered study. We had initially planned to collect prospective and retrospective confidence judgments during problem-solving, but we

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only collected retrospective judgements. In terms of analysis, we had planned to carry out separate repeated measures of ANOVAs to test our hypotheses. However, we decided to analyze our data testing multilevel mixed-effect models and made changes on the OSF page accordingly. We preregistered most of our analyses that we report here. Additional to the preregistered analysis plan, we also conducted some exploratory analyses examining how the difficulty of the problems affected confidence and accuracy in gesture and control groups in interaction with participants' sex. We also tested new models considering sample characteristics (i.e., excluding spontaneously gestured participants from the sample) and trial-related factors. The data, explanations regarding the changes in the procedure and analyses, R code, and additional appendices will be available on the study's OSF page upon acceptance for publication (https://osf.io/6e3fn/).

Participants

We determined the sample size by conducting an a priori analysis using GPower version 3.1 (Faul et al., 2007) since we initially planned to analyze our data with F-tests, conducting separate ANOVAs. Results indicated that the required sample size to achieve 95% power for detecting a medium effect ($d = .05$) at a significance criterion of $\alpha = .05$ was $N = 54$. The effect and planned sample size followed the previous studies that tested individual differences (e.g., age, sex) in mental rotation task performance (e.g., Ariel & Moffat, 2018; Voyer et al., 1995; Voyer, 2011) and that used a similar task (e.g., Chu & Kita, 2008, 2011; Göksun et al., 2013). Considering the potential attrition due to technical issues during online Zoom meetings and our additional objectives of controlling for possible moderating factors, we decided to increase the sample size by approximately 20% and planned to collect data from sixty-five participants.

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However, we analyzed our data, creating multilevel mixed-effect models. Power analysis for linear multilevel mixed models is complicated, with no rule to follow (e.g., Meteyard & Davies, 2020). What is generally recommended is to have as many sampling units as possible. Fewer sampling units point to more significant uncertainty in estimating fixed effects, random effect variances, and cross-level interactions, which is the main limitation on power (see Bell et al., 2010; Scherbaum & Ferreter, 2009; Snijders, 2005). According to Scherbaum and Ferreter (2009)'s study that they examined a range of simulation studies, enough sampling units for multilevel mixed effect models changes between 900 to 2500 data points, meaning 30-50 participants and 30-50 trials detecting an effect size $d = 0.3\text{-}0.4$ for psychological research. Westfall et al. (2014) also suggest that 30 participants performing a psychological task with 30 trials, corresponding to 900 data points, has a power of 0.25 for a small effect size (0.2) and 0.8 for a medium effect size (0.5).

In our study, we reached the planned sample size ($N = 65$, 35 female, age range: 18-35). However, we removed six participants' data from the analyses due to the technical issues experienced during the experiments (e.g., problems saving the data file or video recordings). Relatedly, we completed analyses with a sample of 59 participants ($M_{age} = 21.67$) with normal or corrected-to-normal vision and with no history of neurological disorders. Fifty-nine participants responded to a problem-solving task with 24 problems, making up 1416 sampling units, which is compatible with the suggestions (e.g., Scherbaum & Ferreter, 2009; Westfall et al., 2014) and the previous metacognition studies that used multilevel mixed effect models (e.g., Frank & Kuhlmann, 2016; Lajoie et al., 2020; Pescetelli et al., 2016; Whatley et al., 2021).

Specifically, 31 participants (18 females, 13 males) were tested in the control condition, and 28 participants (14 females, 14 males) were tested in the gesture condition.

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Participants were recruited based on convenience sampling and via the subject pool of Koç University, for which they were given course credits. Ethical approval was obtained from the Institutional Review Board of Koç University (Ethics Code: 2021. 031.IRB3.012) on January 28, 2021.

Measures

Mental Rotation Task

To assess mental rotation task performance and related confidence judgments, we used Chu and Kita's stimuli set (2011) with their permission. We programmed the task using a Python-based package, PsychoPy (Peirce et al., 2019).

In their well-validated task, Chu and Kita (2011) used Shepard and Metzler's (1971) type three-dimensional objects that they created with a free 3D graphics creation software called Blender (see www.blender.org). Each stimulus consists of two 3D objects at the top of the screen and one at the bottom in the experimental set. The upper left and upper right objects are mirror images of each other on the vertical axis. They are always in the canonical position, meaning that their sides are parallel to the horizontal axis, the vertical axis, or the axis pointing to depth. The lower object is a rotated version of one of the upper images by four angles (60°, 120°, 240°, and 300°) around the bisector that goes through the object's center between the horizontal and vertical axis (XY axis), the horizontal and in-depth axis (XZ axis), and the vertical and in-depth axis (YZ axis).

Our experimental task consisted of 24 trials (Left vs. Right x 4 angles x 3 axes) as Chu and Kita’s (2011). Participants solved mental rotation problems by choosing the rotated version of the lower object among the two upper images on the screen. In half of the trials, the lower object was turned from the upper-left object, and in the remaining half, it was turned from the upper-right object. Participants indicated their answers using their keyboard (i.e., pressing "a" for the left image, pressing "s" for the right image). Different from Chu and

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Kita (2011) 's study, in our task, participants evaluated their confidence in their answers after each trial, using a scale from 0, "not confident at all" to 100, "very confident." (See Figure 1 for the schematic display of the task).

--- Insert Figure 1 about here ---

Spatial Problem-Solving Task

We used a similar task to Chu and Kita's (2011) mental rotation task to assess and control for the metacognitive efficiency of the participants in our analyses. The task was adapted from Jost and Jansen (2020) and programmed using PsychoPy (Peirce et al., 2019). We used the stimuli and the code to generate individual figures that were made available in different libraries of cube figures by Peters and Battista (2008) and Jost and Jansen (2020).

In this task, participants solved spatial rotation problems. In each trial, two 3D objects, mirror images of each other on the vertical axis, were presented at the top, and one 3D object was presented at the bottom of the screen. The lower object was a rotated version of one of the upper images by four angels (45°, 90°, 135°, and 180°) around the bisector that goes through the object's center between the vertical (y-axis) or the in-depth axis (z-axis). In half of the trials, stimuli were rotated around the vertical axis; in the other half, they were rotated around the in-depth axis. Every 15-trial included a different rotation in terms of angle rotation (45°, 90°, 135°, and 180°). There were self-paced pauses between the trials, and stimuli presentation was randomized across experimental sessions. Participants indicated their answers using their keyboard (i.e., pressing "a" for the right image, pressing "s" for the left image). After each answer, they evaluated their confidence in their solutions using a scale ranging from "0" (not confident at all) to "10" (very confident).

The task consisted of practice and test phases. During the practice, participants performed four trials and received feedback about their performance presented to them for

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1000 ms (i.e., right vs. wrong). The main task consisted of 60 trials with two blocks, 30 trials each. During the test phase, we gave no feedback to the participants. Instead, a fixation cross ("+") was shown at the center of the screen for 400 ms. Stimulus images were sized 400px x 400px and were presented in a horizontal layout with a vertical shift on a black background in both phases.

Procedure

Due to the COVID-19 pandemic, we collected this study's data online. We administered PsychoPy-programmed tasks via Pavlovia (https://pavlovia.org/), an online platform for remote data collection.

We collected data in two sessions. First, the Pavlovia link of the spatial problem-solving task that we used to assess metacognitive efficiency was shared with the participants. We wanted to control for the metacognitive efficiency scores of the participants in our attempts to examine whether the gesture-cognition link is metacognitively monitored. Therefore, it was essential to administer this task to all the participants first. Participants were asked to complete the task in a quiet room before the main experimental session. They completed the first task at a time of their choice, then contacted the experimenters for the upcoming session.

One week after completing the first spatial problem-solving task assessing metacognitive efficiency, we arranged Zoom meetings with the participants for the second session via email, including information about the second session’s procedure. Participants were asked to be in a quiet room throughout the second session to increase efficiency in the task and were informed about the video recordings. We tested participants in either gesture or control conditions, and recorded videos of all, irrespective of the condition. Empirical evidence suggests that people spontaneously produce co-thought gestures, especially when

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they have difficulties solving spatial problems (e.g., Chu & Kita, 2011). Accordingly, we recorded all participant sessions and coded spontaneous gesture use in the control group in addition to the gestures produced by the participants in the gesture group. Once the Zoom session started, the participants were asked permission for the video recordings. Gesture group participants were instructed about gesture use during the task and were explicitly asked to be in clear sight during the session. In the control group we did not want to miss any possible uses of gestures out of sight. To avoid that, instructions given to control group participants did not refer to any gesture use; however, they were asked to keep a comfortable distance to the computer so they could be seen clearly throughout the video recordings.

After we started video recordings, we shared the Pavlovia link with the participants. Participants solved 24 mental rotation problems, determining whether the lower object was the same as the upper left or right object. In the gesture condition, the participants were given the following instructions by the experimenter: "Try to solve the problems as accurately as possible and use your hand gestures to help you do so in each trial." They were also shown how to use their hands as if holding and rotating an object. In this way, participants learned how using their hands can help with problem-solving. We did not give any instructions to the participants tested in the control condition regarding the strategies they might use. Instead, we only told them to solve the problems as accurately as possible. After each trial, participants evaluated their confidence in their answers using a scale from 0 (not confident at all) to 100 (very confident). There were no trials at the beginning, and we gave no feedback to the participants throughout the task.

The participants completed the first session in about 35 to 40 minutes, and the second lasted approximately 30 minutes.

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Gesture Coding

The first author coded the gestures produced by the participants via the video annotation software ELAN (Lausberg & Sloetjes, 2009). We used McNeill's gesture categorization (1992) to code representational gestures representing semantic information. Representational gestures can represent information by depicting concrete entities like actions or objects (iconic gestures). They may reference specific objects or locations (deictic gestures) or represent abstract ideas (metaphoric gestures). In line with the hypotheses of this study, we only coded and analyzed iconic gestures depicting actions or objects (e.g., an L-shaped gesture to represent the internal structure of the object or a curved handshape gesture to represent the entire structure).

Just after the data collection, 10 participants' data were randomly picked and coded by the first author and a second independent coder to test coding reliability. The intraclass correlation coefficient (ICC) was calculated to assess the reliability using a two-way mixed effects model. The results revealed a high degree of reliability between coders. The average measure ICC was .971 with a 95% confidence interval from .940 to .984 (F (238, 238) = 44.256, $p < .01$. The disagreements were solved through discussion, and criteria were set from the beginning to code the rest of the video files.

Results

Descriptive Statistics on Gesture Use

The participants produced 3156 gestures in 1176 trials during the main mental rotation task. Only the gesture group participants were asked to use their hands in problem-solving. Still, three participants in the control group spontaneously produced gestures, and the total number of gestures they produced was 10.36% of the total number of gestures produced by all participants in the study. The limited percentage of spontaneously produced gestures

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and the limited number of participants who produced them made it hard to evaluate whether spontaneous gesture use also contributed to accuracy and confidence in the task. Therefore, we did not include spontaneous gestures produced by the participants in our analyses in which we examined how the total number of produced gestures interacted with accuracy and confidence. In Table 1, the descriptive statistics of gestures based on condition and sex are summarized.

--- Insert Table 1 about here ---

Descriptive Statistics on Metacognitive Efficiency Scores

We calculated the participants' metacognitive sensitivity (meta d’) and efficiency (MRatio) scores based on a signal-detection theory (SDT) framework (Barett et al., 2013). First, we quantified the metacognitive sensitivity (meta d’) scores following Maniscalco and Lau's (2014) meta-d' analysis, running the code by Lee (2019) (see http://www.columbia.edu/~bsm2105/type2sdt/fit_meta_d_MLE.py) in MATLAB R2021a (The MathWorks Inc., Natick, USA). This quantification allowed us to separate sensitivity (i.e., the degree of successfully discriminating between correct and incorrect responses) and response bias (i.e., the likelihood of a participant endorsing responses with high or low confidence) in metacognitive performance.

Meta d' is a response bias-free measure that evaluates confidence judgments' reliability. However, it is also on the same scale as the Type 1 (e.g., task performance) sensitivity measure “d"“ and may scale with performance (e.g., Fleming & Lau, 2014). Therefore, it is more informative to estimate the metacognitive efficiency levels of the participants relative to their task performance, especially when the goal is to compare metacognitive monitoring across groups or conditions (e.g., Fleming & Lau, 2014; Ordin &

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Polyanskaya, 2021). Considering this, we calculated the participants' metacognitive efficiency scores (i.e., MRatio) by dividing the meta d' to d' ratio and created an index of metacognitive performance that considers the individual level of task performance.

We could not calculate 11 participants' MRatio scores in MATLAB using the code, possibly due to the excessive rates of correct and incorrect answers or participants recurrently giving the same confidence judgments. We excluded 3 participants' data from the analyses after we detected that the first or second order hit rates or false alarm rates were extreme (<0.025 or >0.975). This decision was made following Arbuzova et al. (2022) and considering that such extreme values prevent a stable estimation of SDT-based measures (Shekhar & Rahnev, 2021).

The average metacognitive efficiency scores (M-Ratio) for the spatial problem-solving task were 0.13 (*SE* = .10) for the gesture participants (*N* = 26, 13 females) and 0.20 (*SE* = 0.15) for the control group participants (*N* = 19, 12 females). A score of 1 indicates an ideal relationship between performance and confidence, and the degree of meta d'/d' < 1 refers to the degree to which a participant is metacognitively inefficient. We compared the metacognitive efficiency scores of the participants across conditions by conducting a one-way ANOVA. The results revealed no significant differences between the groups regarding the metacognitive efficiency scores, *F* (1,44) = .133, *p* > .05.

Main Analyses

To test our hypotheses, we created multilevel mixed-effects models with the lme4 (Bates et al., 2014) package in R (version 4.0.4, R Development Core Team, 2020). Multilevel mixed-effects models differ from the classical regression models in which only fixed effects are tested. We treat data points independently when we have only fixed effects in models. However, data is primarily nested because they are produced by the same

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participants or are grouped by some other characteristics. Mixed-effects models incorporate nested data structures of the data and are increasingly used in the literature (Luke, 2017).

We computed statistical significance using the *lmerTest* package (Kuznetsova et al., 2013). We scaled continuous predictor variables following Bates et al. (2014). The aim of this was to avoid convergence problems for fitted models and to facilitate interpretation. For the comparisons between variables, including categorical predictors, we used *emmeans* and *contrast* functions of the *emmeans* package in R (Lenth et al., 2019). The interactions involving continuous predictors were tested and plotted with the *probe_interaction* function of the *interactions* package. We visualized the interactions using the *interact_plot* and *cat_plot* functions of the *ggplot2* package (Wickham, 2006). We compared different models' significance by conducting chi-square tests (i.e., likelihood ratio tests) and evaluated variable contributions to the tested models with the *Anova* function of the *car* package.

In the first line of analysis, we compared gesture and control groups. In the second line of analysis, we focused on the gesture group only. In all models we tested, we included random effects of subjects (i.e., some participants could be more successful in mental rotation tasks) and trials (i.e., some trials could yield more errors and influence monitoring) to avoid losing important information about variability within participants or within items, thus increasing statistical power (Brown, 2021). Metacognitive efficiency scores (i.e., MRatio) were added to the models as a control variable. In the third line of analysis, we tested new models to understand and explain the data better, considering sample characteristics and trial-related factors (see Supplementary Material).

Analyses Comparing Gesture and Control Groups

The analyses that we conducted to compare gesture and control groups comprised two groups of multi-level mixed effect models: one with the accuracy (i.e., correct or incorrect

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answers to the questions) and the other with the decision confidence judgments as the outcome variables. For the accuracy analyses, the logistic version of the models was created, considering that accuracy is binary as an outcome variable.

First, we created intercept-only null models for the accuracy and confidence analyses separately, regressing the outcome variable (i.e., accuracy or confidence) on random effects of trials and subjects. Next, we consecutively added our control variable MRatio to the models and added fixed effect variables. We compared each model with the previous one that included all the variables except the lastly added fixed effect to see whether the inclusion of the new predictor makes the model significantly better at explaining the variance.

Accuracy Comparisons between Gesture and Control Groups

We included answers to 24 problems in the mental rotation task for accuracy analyses, which yielded 1416 responses (24 items*59 participants). Of these, 1307 (92.30%) of the responses were correct. The comparison between the null and last models revealed significant improvement in the previous model's variance, $\chi2(16) = 132.16$, $p < .001$. Since the results showed improvements in each model with a new fixed effect, the last model was accepted and reported below.

Our last mixed-effects logistic regression model included accuracy as the outcome variable, group, difficulty, sex, and confidence as the fixed effects, MRatio as the control variable, and subjects and trials as the random effects. The results revealed significant main effects of problem difficulty, $\chi2(1) = 4.64$, $p < .05$, and confidence, $\chi2(1) = 21.26$, $p < .001$. We found that easy problems predicted accuracy in answers by 1.43 ± .66. Higher confidence judgments were also associated with accuracy by 0.38 ± .08. Group and sex interaction was not significant, $p = 07$. Still, the interaction between problem difficulty and confidence significantly predicted accuracy. The results revealed that difficult problems were evaluated

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with lower confidence, and they predicted lower task accuracy by -0.31 ± .09, $\chi2(1) = 11.08$, $p < .001$. Lastly, we observed a significant three-way interaction between group, sex, and confidence variables, $\chi2(1) = 6.23$, $p < .05$. Simple slope analysis revealed that for female participants, confidence predicted accuracy both in the gesture and control groups; however, confidence predicted accuracy only in the control group for male participants. Being female and having low confidence in answers decreased task accuracy in both conditions by -0.62 ± .0.25 (see Figure 2).

The summarized analyses showed that the group itself does not predict task accuracy. Instead, accuracy was predicted by combining the difficulty of the problems, sex, and confidence in answers. As expected, easy problems were answered more correctly than difficult problems. Being a female was associated with lower task accuracy than being male. Confidence and accuracy increased parallel in the control group for males and females. But in the gesture group, confidence and accuracy increased in parallel only for the females. Males in the gesture group gave compatible confidence judgments across trials irrespective of their correct and incorrect answers (see Figure 2 and Table 2 for a summary of the final logistic mixed effect model`s estimated coefficients and related standard errors).

--- Insert Figure 2 about here ---

--- Insert Table 2 about here ---

Confidence Comparisons between Gesture and Control Groups

The same line of analyses was also carried out, taking confidence as the outcome variable. As in the accuracy analyses, confidence was assessed by creating multilevel mixed-effects models consecutively. Test variables were added to the models as fixed factors one by one. Considering the significant improvement in the last model compared to the null model and the models that precede it, we decided to report only the last model, $\chi2(15) = 177.21$, $p < .001$.

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The last multi-level mixed effect model predicting confidence as the outcome variable included group, difficulty, sex, and accuracy as the fixed effects, MRatio as the control variable, and subjects and trials as random effects. The results revealed a significant main effect of accuracy in predicting confidence judgments, $\chi 2(1) = 15.88$, $p < .001$, indicating that the participants evaluated their correct answers with higher confidence by 1.08 ± .27. The group and accuracy interaction were not significant, $p = .08$. We observed a significant interaction between problem difficulty and accuracy, $\chi 2(1) = 7.17$, $p < .01$. This interaction suggested that incorrectly answered difficult problems predicted decreases in confidence judgments by -.97 ± .36. Lastly, we observed a significant three-way interaction between group, sex, and accuracy, $\chi 2(1) = 9.21$, $p < .01$. When compared to the correct answers, incorrect answers were evaluated with lower confidence judgments by females and males in the control group by -1.93 ± .74. Males evaluated their correct answers similarly in both gesture and control conditions. For females, a different pattern emerged. They evaluated their correct answers with higher confidence in the gesture group compared to the control group (see Figure 3 and Table 3 for a summary of the final logistic mixed effect model's estimated coefficients and related standard errors).

The results of the consecutive models created to predict confidence in answers were compatible with the results we had from the accuracy analyses. In general, participants evaluated their correct answers with higher confidence than their incorrect answers. Being in the control group predicted lower confidence when accuracy and sex were considered. In the gesture group, confidence judgments were higher than in the control group. Especially female participants evaluated their correct answers more confidently if they were in the gesture group.

--- Insert Figure 3 about here ---

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--- Insert Table 3 about here ---

In these two lines of analysis, we first took accuracy and then confidence as the outcome variable. Theoretically, accuracy and confidence represent object-level and meta-level, respectively. They are assumed to be in continuous interaction during cognitive processing (e.g., Maniscalco & Lau, 2014; Mitchum & Kelley, 2010). Object-level (accuracy) informs meta-level (confidence) about performance efficiency, and meta-level changes the object-level performance by employing new ways of dealing with the task at hand. With these analyses, we aimed to see whether confidence and accuracy interact differently with variables of sex and group. The results showed that both confidence and accuracy interacted with sex and group variables in predicting the other, proving that they are in a reciprocal relationship, as theoretically suggested. Also, when we took accuracy as the outcome, we observed that confidence predicted accuracy for females in both gesture and control groups. In contrast, it predicted accuracy for males only in the control group. Analyses with confidence as the outcome showed that in the gesture group, gesture manipulation increased males' confidence in their incorrect answers, specifically extending the previous results.

Gesture Group-Only Analyses

In the second line of analyses, we tested the previously mentioned multi-level consecutive mixed-effects models with the gesture group only. The aim was to see whether the total number of gestures (i.e., gesture frequency) was significant in predicting accuracy, confidence, or both.

Accuracy in the Gesture Group

Accuracy was assessed by creating multiple mixed-effects logistic regression models as in the previous analyses. We included answers to 24 problems in the mental rotation task

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for accuracy analyses in the gesture group from 28 participants. After we deleted the missing data points list-wise, it yielded 660 responses instead of 672 (24 problems * 28 participants). Of these, 512 (77.58%) of the responses were correct.

The last mixed-effect model included accuracy as the outcome variable, MRatio as the control variable, gesture frequency, confidence, problem difficulty, sex as the fixed effects, and subjects and trials as the random effects. In predicting accuracy in the gesture group, gesture frequency was not significant, $p = .08$. The main effect of confidence was significant in predicting accuracy in the gesture group, $\chi2(1) = 21.52$, $p < .001$. Higher confidence predicted higher accuracy by 1.32 ± .28. Problem difficulty was also significant in predicting accuracy, $\chi2(1) = 6.50$, $p < .05$. Difficult problems were associated with lower task accuracy by -0.92 ± 0.36. We observed significant interactions of confidence and problem difficulty, $\chi2(1) = 6.86$, $p < .01$, gesture frequency and sex, $\chi2(1) = 3.96$, $p < .05$, and confidence and sex variables, $\chi2(1) = 5.47$, $p < .05$. The significant interaction of confidence and problem difficulty showed that the participants evaluated hard problems with lower confidence, and it predicted lower task accuracy by −.47 ± .22. The significant interaction between gesture frequency and sex showed that for males, the increased number of gestures was associated with lower task accuracy by −1.04 ± .52. In contrast, increasing gesture production predicted higher task accuracy in females. The significant interaction of sex and confidence suggested that females, in general, were less confident in their answers, and that predicted lower accuracy in the task by −1.03 ± .44.

These analyses showed that the total number of gestures produced by the participants during problem-solving does not predict task accuracy itself. Instead, problem difficulty, sex, and confidence predicted accuracy in the gesture group as in the previous analyses. The contribution of these new analyses was that they indicated a sex difference in gesture

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production during mental rotation task performance. In general, females produced more gestures during problem-solving than males, and it predicted accuracy in the task, meaning that they benefited from using gestures. The reverse was true for the males. They produced fewer gestures than females, and their increasing gesture production was associated with lower accuracy. Males' task performance was not positively affected by gesture use. Instead, it was worsened by this external instruction to use gestures. (See Figure 4 for the two-way interactions and Table 4 for a summary of the final mixed effect model's estimated coefficients and related standard errors).

--- Insert Figure 4 about here ---

--- Insert Table 4 about here ---

Confidence in the Gesture Group

Lastly, we created the same multilevel mixed-effects models to predict confidence as the outcome variable in the gesture group. A significant improvement was observed in the last model, compared to the intercept-only null model, $\chi 2(15) = 108.22$, $p < .001$. The initial model included subjects and trials as the random effects, MRatio as the control variable, and gesture frequency, accuracy, difficulty, and sex as the fixed effects. The results revealed that gesture frequency was not significant in predicting confidence as itself, $p = .09$. Accuracy predicted confidence judgments in the gesture group, $\chi 2(1) = 25.84$, $p < .001$. Specifically, the participants judged correct answers more confidently by 2.21 ± .44. The main effect of sex was significant, $\chi 2(1) = 11.27$, $p < .001$, showing that males were confident in their answers in general compared to the female participants by 2.15 ± .64. The interactions between gesture frequency and difficulty and accuracy and difficulty were not significant in predicting confidence judgments (*p's* = .09, .07, respectively). The accuracy and sex interaction significantly predicted confidence, $\chi 2(1) = 6.26$, $p < .05$. This result suggested that

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females evaluated their incorrect answers with lower confidence than their correct answers by -1.55 ± .62. These results enhanced previous results by showing that sex, even though it did not predict accuracy by itself, predicted confidence in the gesture group. (See Figure 5 for the two-way interactions and Table 5 for a summary of the final mixed effect model's estimated coefficients and related standard errors).

--- Insert Figure 5 about here ---

Discussion

In this study, we investigated whether (1) mental rotation performance can be enhanced by encouraging gesture use in participants during problem-solving and (2) the metacognitive system would monitor this potential positive influence of gestures in spatial thinking. With this aim, participants solved mental rotation problems and evaluated their confidence after each solution in gesture or control conditions. We assessed our participants' baseline metacognitive efficiency levels in a separate mental rotation test and controlled for it in our analyses. Research has evidenced co-thought encouraged gestures' effects on facilitating the manipulation of spatial-motoric input (i.e., mental rotation performance, Chu & Kita, 2011; Erhlich et al., 2006); however, their influence on the monitoring of the underlying mental states remains unexplored. This study was the first to investigate the interactions between gestures and metacognitive monitoring of spatial thinking.

Our results showed that the participants had sufficient metacognitive monitoring ability of spatial mental rotation. They were more confident in their correct answers than their incorrect answers, and their answers to easy than difficult problems. Consistently, the participants were more accurate in answering easy problems than difficult ones. These results indicated that the participants successfully regulated their confidence judgments by considering internal signals and task-related variations (i.e., difficulty), replicating previous

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studies that reported correspondence between task performance and confidence judgments during spatial thinking (e.g., Ariel et al., 2018; Ariel & Moffat, 2018; Cook-Simpson et al., 2007; Thomas et al., 2012). We also observed the variations in performance and confidence between the gesture and control groups. In the gesture group, mean performances and confidence judgments were higher than in the control group. These results evidenced the facilitatory role of producing gestures during problem-solving consistently with the previous studies (e.g., in adults, Chu & Kita, 2008, 2011, 2014; So et al., 2014; in children, Ehrlich et al., 2006), supported our hypotheses, and extended the literature in significant ways.

Specifically, we observed that cues aroused by encouraged uses of gestures influence cognitive processing, possibly interacting with confidence during spatial thinking. This new finding extends the literature by showing that motor system activation likely has a bottom-up influence on metacognitive processes. From a perspective, this result is in line with several previous studies (e.g., Alban & Kelley, 2013; Allen et al., 2016; Fleming et al., 2010, 2014; Hildenbrand & Sanchez, 2022; Palser et al., 2018), reporting that haptic or proprioceptive cues can influence how the metacognitive system monitors the content. For instance, Alban and Kelley (2013) showed that judgments of learning (JOLs) for to-be-remembered words increased as the perceptual experiences of weight during learning increased. In Palser and colleagues' study (2018), people felt more confident when they were primed to move faster in making their perceptual decisions than at a natural pace, and this was more of a case for their incorrect responses. Several other studies also evidenced the motor system's contribution to confidence judgments. Fleming et al. (2014) reported that disruption of the motor system adversely affects metacognitive monitoring in perceptual discrimination, and Allen et al. (2016) observed that manipulations of autonomic arousal modulate confidence on a motion-discrimination task. The current study is qualitatively different from the mentioned studies regarding methodology and the cognitive processing it examined. Previous studies

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mainly focused on memory processes and perceptual decisions and examined metacognitive monitoring of such processes during tasks that required whole-body movements by the participants. Still, our results are parallel and indicate that proprioceptive and interoceptive states influenced by the motor systems activation (e.g., by encouraging moving faster or using gestures) serve as cues guiding confidence. Together such results show that metacognition is not removed from perception and action. Instead, it is in close interaction with them. This view adds to the traditional views of metacognition, which primarily focus on the top-down influences on individuals' motor behavior (i.e., Baranski & Petrusic, 1998; Palser et al., 2018), and highlights the importance of including the influences of bodily-aroused motor information in the theoretical explanations of metacognitive processes.

When we conducted additional analyses to understand the determinants of gestures' effects on confidence, we saw that we need to consider the interactions between individual and task-related variations in defining gesture-related effects on cognition and metacognition, in alignment with the recent discussions in the literature (for a review see Özer & Göksun, 2020). We observed that encouraging gestures did not enhance performance and confidence by their mere production. Gestures facilitated task performance but not when the problems were easy, and the participants already performed well with great confidence (i.e., in males). Instead, gestures enhanced the accuracy and confidence of those who needed them. Specifically, being in the gesture group was more of an advantage for females than males. Females in the gesture group were more confident in their correct answers than females in the control group. They felt more confident and became more accurate as they gestured, as we hypothesized. The trend was the opposite for males, and it was unexpected. Confidence judgments predicted the accuracy of males' mental rotation task performance only in the control group. In the gesture group, the encouraged use of gestures increased males'

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confidence in their incorrect answers, reversely affecting metacognitive monitoring of spatial mental rotation. Males felt less confident and became less accurate as they gestured.

There are possible explanations for these results. Empirical evidence defines the variations in visual-spatial working memory (WM) as one of the reasons underlying the sex differences in spatial abilities, especially in mental rotation (e.g., Kaufman, 2007; for a meta-analysis, Voyer et al., 2017; Wang & Carr, 2014). Consistently, in the gesture literature, gestures' compensatory role for those with the most heavily taxed resources is discussed (e.g., Chu et al., 2014; Eielts et al., 2020; Gillespie et al., 2014; Göksun et al., 2013; Hostetter & Alibali, 2007; Smithson & Nicoladis, 2013; for a review, Özer & Göksun, 2020). We did not explicitly assess the spatial WM abilities of the participants in this study, and they cannot fully account for the sex differences in spatial abilities. Still, based on the meta-analysis by Voyer and colleagues (2017) reporting consistent small magnitude differences between males and females in spatial WM, we speculate that maybe the females in our study were lower in visual-spatial WM than males and the gesture manipulation made them better at holding the spatial information in their WM by reducing the cognitive load (e.g., Goldin-Meadow & Wagner, 2005). One needs to monitor their thought processes to accurately evaluate performance while engaged in a task. However, such monitoring is hard if the task is novel or challenging, imposing a high cognitive load on the individual (van Merriënboer & Sweller, 2005). Voyer et al. (2017) suggest that the evidenced differences between males and females in visual-spatial WM abilities may make females more prone to monitoring difficulties in spatial domains. In our study, gestures probably acted as a compensatory tool for females by reducing the cognitive load and preventing them from experiencing monitoring difficulties. Reduced cognitive load paved the way for increased fluency and availability of cues with which people make metacognitive judgments, and in this way, gestures increased confidence, especially in females.

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Kita et al. (2017) suggest that gestures activate, manipulate, and explore new spatial-motoric representations, and these functions are not mutually exclusive. Our study does not allow us to define the exact ways that gestures exerted their influence on spatial mental rotation. However, in line with Kita et al. (2017), we believe that gestures activated richer spatial-motoric representations and helped females manipulate the object in their minds by providing new ways of exploring it. One other possibility is that gestures changed females' strategies, making them better at encoding object parts and attending to the entire object (i.e., analytic strategy) rather than to the different pieces of an object to compare them with the response alternatives (i.e., holistic strategy). Males generally pursue an analytic strategy in solving mental rotation problems, whereas females use a holistic strategy. This difference in strategy selection has been closely linked to performance (e.g., Hegarty et al., 2018; Stieff et al., 2014; Xu & Franconeri, 2015). Among the different stages of solving mental rotation problems (i.e., processing and identifying the stimuli, rotating it, and deciding on an answer), visual rotation is crucial in predicting better spatial mental rotation performance (Boone & Hegarty, 2017). Insightfully, we believe that gestures have improved the processing in the rotation stage by changing strategies and making this process available to the participants through increased fluency and availability cues. As far as we know, there is only one study by Alibali and colleagues (2011) that previously documented gestures' influence in changing strategies (i.e., in predicting gear movements). Future studies can control for interindividual variations (i.e., spatial, visual WM) and assess strategy selections in males and females with either self-reports or eye-tracking data to determine precisely how gestures influence mental rotation performance and related confidence.

The results we obtained for males pointed to some mixed or even detrimental effects of encouraging gestures on performance and confidence measures. Recently Oviatt et al. (2021) reported that physical activity levels provide information about one's domain

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expertise. They analyzed spontaneous gesture use by mathematics students when explaining problem solutions and found that expertise is associated with reduced gesturing characterized by briefer duration and slower velocity. Non-experts produced more gestures irrespective of the difficulty level than experts. Experts produced fewer gestures in total, but the number of iconic gestures they produced was higher than those produced by non-experts. Our study's problem type was different (i.e., mathematical problems vs. mental rotation), but Oviatt et al. (2017) 's findings support our results. Their findings indirectly suggest that experts have this accurate insight into their abilities (i.e., better metacognitive monitoring) and strategically employ the right gestures (i.e., more iconic gestures by experts) when needed. In our study, males were already doing well, but we made them use their gestures during problem-solving, giving them a strategy they did not need. This manipulation adversely affected their performance. Despite this effect, males' confidence in their incorrect answers increased in the gesture group, revealing that the encouraged use of gestures had an illusory positive effect on their metacognitive monitoring. In one of the previous studies, Palser and colleagues (2018) primed their participants to move faster than they would move during a perceptual decision task and found that the participants felt more confident about their incorrect responses when primed to move faster. They interpreted this result as that altering individuals’ kinematics adversely affects their ability to infer their confidence. Maybe our gesture encouragement also altered males’ already well-functioning problem-solving process and disrupted performance monitoring. Our design does not permit us to explain what males experienced when producing gestures. However, it is a valuable open question to ask in future studies that would also deepen our understanding of the selective facilitatory effects of gestures on cognition and metacognition. Future studies can compare males and females in different spatial domains where we know females outperform males (i.e., object location memory, Voyer et al., 2007) to see whether our findings related to gesture and metacognition would be

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evident in different domains in the same direction. If our speculations are accurate, we should obtain similar findings with reverse directions for males and females.

In this current study, we replicated sex differences in confidence and spatial thinking, the most evidenced difference between sexes in the literature (e.g., Estes & Felker, 2012; Hegarty et al., 2018), but most importantly, we showed that appropriate tools offered to females could immediately influence their confidence and performance in mental rotation. This result supports the socio-cognitive explanations of sex differences (e.g., differences in childhood activities, spatial toy preferences, or gender-based expectations, Baenninger & Newcombe, 1995, Gold et al., 2018; Nazareth et al., 2013) in mental rotation over the neurological or hormonal ones (e.g., Aleman et al., 2004; Hugdahl et al., 2006). Further studies can examine whether the relationships between gestures and confidence change based on the theory-based factors that we know influence online assessments of performance (e.g., perceptions of stereotype threat and self-efficacy beliefs; Jost & Jansen, 2021). It would also be fruitful to examine the same relationships with aging populations or neuropsychologically impaired people performing poorly at spatial tasks and responding differently to gesture use. Such comparisons can help us uncover confidence's role in regulating the relationships between gestures and cognition.

One limitation of the current study is that we assessed confidence on a trial-by-trial basis and focused on males’ and females' subjective perceptions of confidence in their answers in our main experimental task. Due to the reduced number of experimental trials, we could not calculate our main task's reliability indices (e.g., MRatio, bias) (see Maniscalco & Lau, 2014). Therefore, our study does not have any implications regarding gestures' effects on increasing the monitoring efficiency of the participants in mental rotation tasks. Instead, we showed that gesture manipulation made female participants subjectively more confident in their answers, and this probably modulated the relationships between gestures and mental

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rotation task performance. Future studies should elucidate whether gesture use enhances metacognitive efficiency in spatial thinking in different populations, clarifying how long and to what extent we see such influences on cognition and metacognition.

Second, in this study, we had three (two females, one male) control group participants who spontaneously gestured during problem-solving. When we excluded them from our analyses (see Supplementary Material 1.2. for details), group was still not significant in predicting accuracy and confidence, but it interacted with confidence and accuracy in predicting the other. After removing the spontaneously gestured participants from the sample, we observed that both confidence and accuracy were higher in the gesture group, irrespective of the participant's sex. These results suggested that spontaneously gestured participants performed more like gesture group participants in terms of accuracy and confidence. Still, we do not know why these participants gestured when the others did not. Considering Eielts et al. (2020)'s findings pointing to significant influences of encouraged and spontaneous gestures on problem-solving for individuals with a lower visual working-memory capacity, we speculate that these participants can also be the participants with lower visual-working memory capacity. Another possibility is that these participants have higher metacognitive monitoring abilities, using their gestures strategically to increase performance when needed. These speculations are yet to be tested in future studies.

Our primary aim in this study was to understand how the metacognitive system interacts with gestures during spatial thinking. We formed our hypothesis based on the assumption that efficient metacognitive monitoring is attained through increased accessible cues, which we can achieve with encouraging gestures. Thus, different from Chu and Kita's (2011), we only included a gesture-encouraged group but not a gesture-prohibited group in this first study. Given our findings, it is valuable to conduct future studies comparing gesture-encouraged, gesture-prohibited, and control groups in terms of task performance and

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metacognitive monitoring to see whether prohibiting gesture use decreases confidence in spatial performance by partially preventing access to metacognitive cues. Our results suggest that encouraging gestures during problem-solving helped those who could benefit from gesture use and made them more confident. If people use their gestures spontaneously when they feel they need them, then prohibiting them from gesturing should be reflected in their judgments as decreased confidence. Such findings would confirm our claims of an interplay between gestures and metacognition in enhancing cognition.

Lastly, we conducted this study online. To make sure that we captured all spontaneous or encouraged uses of gestures, we asked participants to be clearly seen throughout the sessions in both conditions. During coding, we did not detect any case that made us suspicious of gestures out of sight. However, in some cases, control group participants were holding their hands under their tables and might have produced gestures we missed. Number of online studies after the pandemic have been increasing. Further studies can examine how this potential limitation might affect the interpretation of gesture studies' results comparing gesture production in online versus in-person experiments.

Conclusions

This study is the first to show that gestures interact with confidence in exerting their influence on cognitive processes. We showed that the metacognitive system monitors gestures' effects, particularly during mental rotation. Considering that interventions targeting confidence in spatial thinking could have outcomes for promoting interest and retention in spatial domains, we believe that our results have both theoretical and practical value. We observed the selective positive influence of gestures on females' performance and confidence in spatial thinking. This result highlights the importance of tailoring interventions to increase cognitive processing based on individuals' needs.

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Supplementary Material

The Supplementary Material is available at: qjep.sagepub.com

Data Accessibility Statement

The data from the present experiment are publicly available at the Open Science Framework website: https://osf.io/6e3fn/

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Declaration of Conflicting Interests

The Author(s) declare(s) that there is no conflict of interest.

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Figure Captions

Figure 1. Schematic Display of the Mental Rotation Task with Example Stimuli

Note. The lower object represents the rotated version of the upper-left object about 240 from the bisector of the horizontal and vertical axes. The scale represents the participants' actual scale to make their confidence judgments.

Figure 2. The Relationships Between Log Odds of Accuracy (i.e., correct responding in the task) and Scaled Scores of Confidence Judgments as Factors of Sex (i.e., females, males) and Group (i.e., gesture or control).

Note. The hues around regression lines represent 95% confidence intervals.

Figure 3. The Interaction of Group (i.e., control and gesture), Answer Type (i.e., incorrect, correct), and Sex (i.e., females, males) in Predicting Confidence in Answers

Note. The brackets show 95% confidence intervals.

Figure 4. The Relationships Between Log Odds of Accuracy (i.e., Correct Responding in Task) and Scaled Scores of Gesture Frequency as a Function of Sex

Note. The hues around regression lines represent 95% confidence intervals.

Figure 5. The Interaction of Sex (i.e., Females, Males) and Accuracy (i.e., Correct, Incorrect) in Predicting Confidence in Answers

Note. The brackets show 95% confidence intervals.

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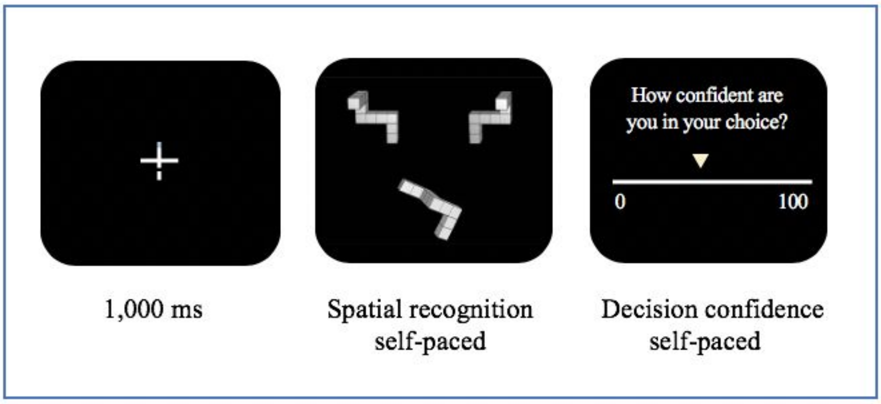

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Note. The lower object represents the rotated version of the upper-left object about 240 from the bisector of the horizontal and vertical axes. The scale represents the participants' actual scale to make their confidence judgments.

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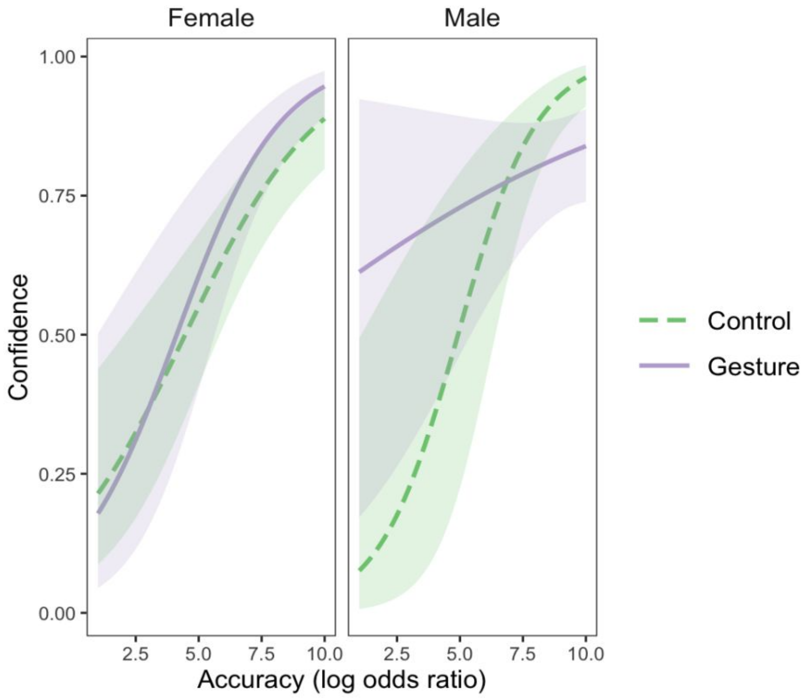

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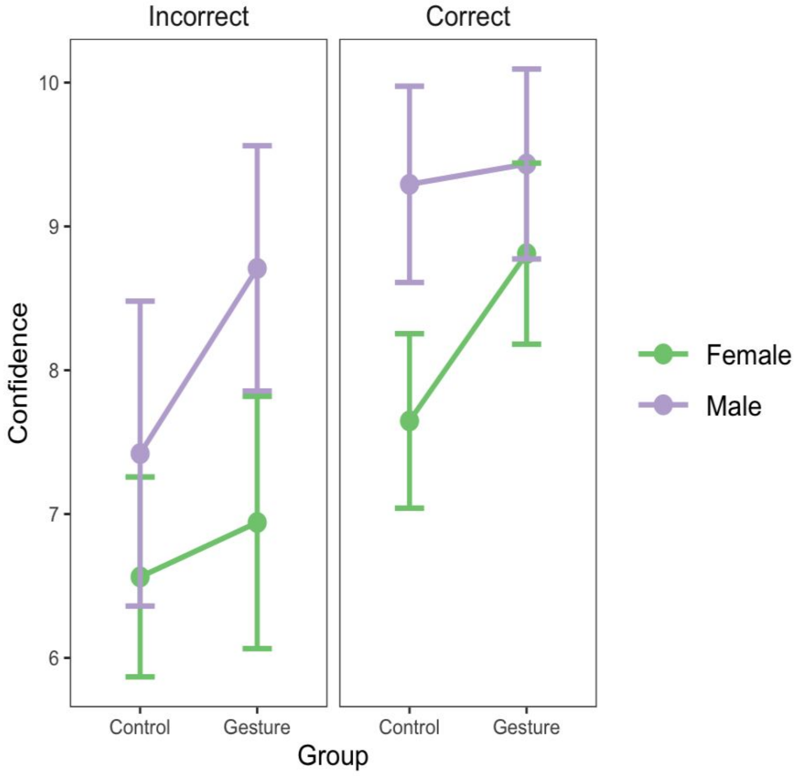

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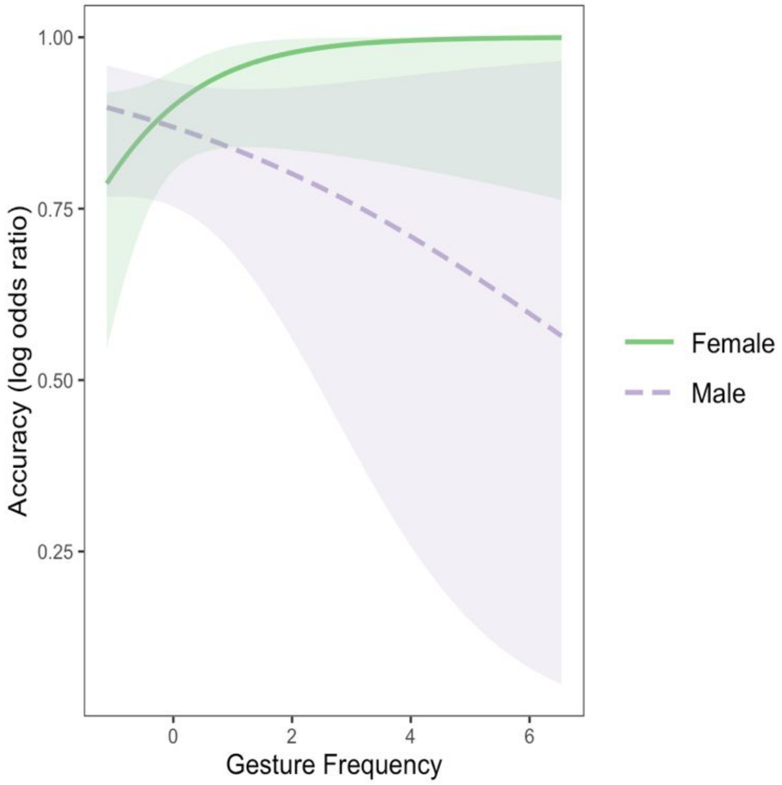

Figure 4. The Relationships Between Log Odds of Accuracy (i.e., Correct Responding in Task) and Scaled Scores of Gesture Frequency as a Function of Sex

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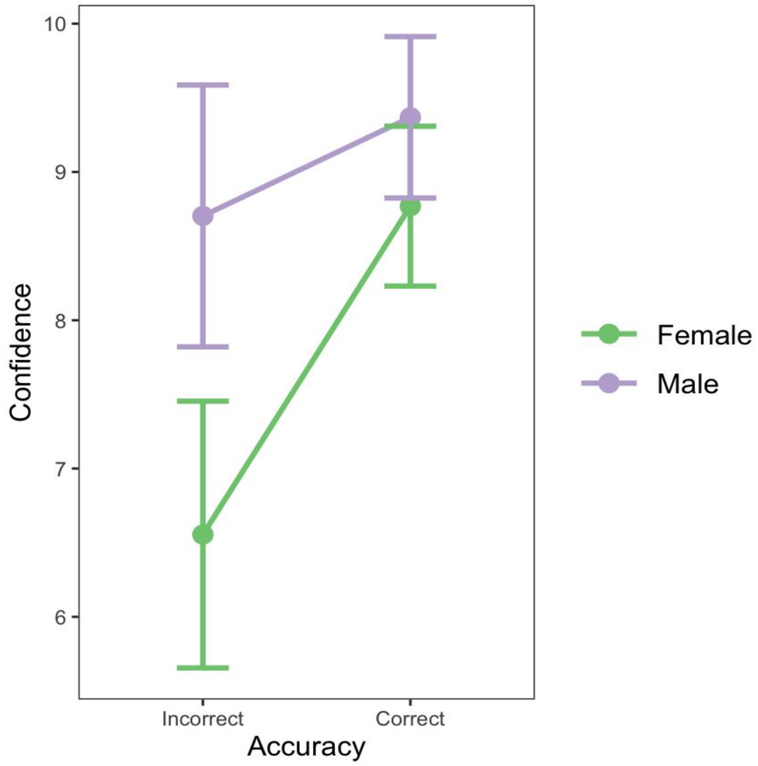

Figure 5. The Interaction of Sex (i.e., Females, Males) and Accuracy (i.e., Correct, Incorrect) in Predicting Confidence in Answers

Note. The brackets show 95% confidence intervals.

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Table 1. Descriptive Statistics of Gestures as a Function of Group and Sex

Iconic Gestures	Experimental Group		
	Control	Gesture	Total
Females	201 (6.37%)	1508 (47.78%)	1709 (54.15%)
Males	126 (3.99%)	1321 (41.86%)	1447 (45.85%)
Total	327 (10.36%)	2829 (89.64%)	3156 (100%)

Note. Columns represent the total number of gestures produced by the participants in gesture and control conditions categorized by sex. The percentage of produced gestures in relation to the total number of gestures produced in the study was given in parentheses.

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Table 2

Model Summary for Task Accuracy Comparing Gesture and Control Groups

	Coefficient	SE
FIXED-EFFECTS		
(Intercept)	-1.67**	.61
MRatio	-0.01	.11
Group	-0.33	1.07
Difficulty	1.43*	.66
Sex	-1.44	1.54
Confidence	0.38***	.08
Group*Difficulty	0.44	1.19
Group*Sex	3.78 †	2.12
Difficulty*Sex	0.06	1.77
Group*Confidence	0.11	.13
Difficulty*Confidence	-0.31***	.09
Sex*Confidence	0.26	.18
Group*Difficulty*Sex	-2.49	2.38
Group*Difficulty*Confidence	0.004	.16
Group*Sex*Confidence	-0.62*	.25
Difficulty*Sex*Confidence	-0.01	.21
Group*Difficulty*Sex*Confidence	0.33	.28
	Variance	
RANDOM-EFFECTS		
Intercepts		
Subjects	5.21	
Trials	1.35	

Note. Significance codes = ****p* < .001, ***p* < .01, **p* < .05, †p < .1.

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Table 3

Model Summary for Confidence Comparing Gesture and Control Groups

	Coefficient	SE
FIXED-EFFECTS		
(Intercept)	6.56***	0.35
MRatio	0.24	0.15
Group	0.38	0.58
Difficulty	0.03	.27
Sex	0.86	.65
Accuracy	1.08***	.27
Group*Difficulty	-0.47	.51
Group*Sex	0.91	.90
Difficulty*Sex	0.83	.59
Group*Accuracy	0.78 †	.46
Difficulty*Accuracy	-0.97**	.36
Sex*Accuracy	0.79	.54
Group*Difficulty*Sex	-1.10	.82
Group*Difficulty*Accuracy	0.23	.59
Group*Sex*Accuracy	-1.93**	.74
Difficulty*Sex*Accuracy	-0.17	.67
Group*Difficulty*Sex*Accuracy	0.78	.93
	Variance	
RANDOM-EFFECTS		
Intercepts		
Subjects	1.256	
Trials	.02	

Note. Significance codes = ****p* < .001, ***p* < .01, **p* < .05, †p < .1.

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Table 4

Model Summary for Accuracy in the Gesture Group

	Coefficient	SE
FIXED-EFFECTS		
(Intercept)	6.56***	.39
MRatio	-0.0006	.22
Gesture Frequency	0.79	.46†
Confidence	1.32***	.29
Difficulty	-0.92*	.36
Sex	-0.30	.56
Gesture Frequency*Confidence	0.32	.48
Gesture Frequency*Difficulty	-0.79	.51
Confidence*Difficulty	-0.85**	.33
Gesture Frequency*Sex	-1.04*	.52
Confidence*Sex	-1.04*	.44
Difficulty*Sex	0.09	.50
Gesture Frequency*Confidence*Difficulty	0.25	.56
Gesture Frequency*Confidence*Sex	0.09	.58
Gesture Frequency*Difficulty*Sex	0.79	.57
Confidence*Difficulty*Sex	0.84†	.50
Gesture Frequency*Confidence*Difficulty*Sex	-0.85	.68
	Variance	
RANDOM-EFFECTS		
Intercepts		
Subjects	0.99	
Trials	.00	

Note. Significance codes = ***p < .001, **p < .01, *p < .05, †p < .1.

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Table 5

Model Summary for Confidence in the Gesture Group

	Coefficient	SE
FIXED-EFFECTS		
(Intercept)	6.56***	.39
MRatio	0.04	.22
Gesture Frequency	-0.52†	.46
Accuracy	0.97***	.29
Sex	0.94***	.36
Difficulty	-0.12	.56
Gesture Frequency*Accuracy	0.50	.48
Gesture Frequency*Sex	0.28	.51
Accuracy*Sex	-0.68*	.33
Gesture Frequency*Difficulty	0.58†	.52
Accuracy*Difficulty	-0.44†	.44
Sex*Difficulty	-0.13	.50
Gesture Frequency*Accuracy*Sex	-0.34	.56
Gesture Frequency*Accuracy*Difficulty	-0.32	.58
Gesture Frequency*Sex*Difficulty	-0.31	.57
Accuracy*Sex*Difficulty	0.34	.50
Gesture Frequency*Accuracy*Sex*Difficulty	0.11	.68
	Variance	
RANDOM-EFFECTS		
Intercepts		
Subjects	0.13	
Trials	.01	

Note. Significance codes = ***p < .001, **p < .01, *p < .05, †p < .1.

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