Consciousness and Cognition 57 (2018) 33–40

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

Altering movement parameters disrupts metacognitive accuracy

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ARTICLE INFO

Keywords:
Metacognition
Confidence

ABSTRACT

Correctly estimating the confidence we should have in our decisions has traditionally been viewed as a perceptual judgement based solely on the strength or quality of sensory information. However, accumulating evidence has demonstrated that the motor system contributes to judgements of perceptual confidence. Here, we manipulated the speed at which participants' moved using a behavioural priming task and showed that increasing movement speed above participants' baseline measures disrupts their ability to form accurate confidence judgements about their performance. Specifically, after being primed to move faster than they would naturally, participants reported higher confidence in their incorrect decisions than when they moved at their natural pace. We refer to this finding as the adamantly wrong effect. The results are consistent with the hypothesis that veridical feedback from the effector used to indicate a decision is employed to form accurate metacognitive judgements of performance.

1. Introduction

Humans are unique amongst animals in being able to provide explicit reports on the reliability of, or confidence in their decisions. Previous studies have demonstrated that our confidence in our decisions or opinions plays a key role in group interactions (Bahrami et al., 2010; Koriat, 2012). Whenever people express an opinion, they are likely to also communicate their confidence in that opinion, be this explicitly through what they say or implicitly in their movements and facial expressions (Aitchison, Bang, Bahrami, & Latham, 2015). Accurate understanding of confidence has obvious implications for high-risk decision making domains such as financial investment (e.g. Broihanne, Merli, & Roger, 2014), medical diagnosis (e.g. Berner & Graber, 2008), jury verdicts (e.g. Tenney, MacCoun, Spellman, & Hastie, 2007), and politics (Johnson, 2004).

Theoretical models of perception have proposed that confidence is related to the quality or strength of sensory processing (Barthelmé & Mamassian, 2010; Kepecs, Uchida, Zariwala, & Mainen, 2008; Kiani & Shadlen, 2009; Vickers, 1979; Zylberberg, Barttfeld, & Sigman, 2012; see Yeung & Summerfield, 2012, for a review) and speak to a domain-specific formation of confidence judgements. However, there is increasing evidence that perceptual-decision signals are also seen in neural circuits specialised for motor actions (Cisek & Kalaska, 2005; Freedman & Assad, 2011; Hernández, Zainos, & Romo, 2002; Romo, Hernández, & Zainos, 2004; Shadlen & Newsome, 2001), suggesting a contribution of the motor system to estimates of confidence, and supporting the idea of metacognition as a domain-general process. Indeed, it has recently been shown that disruption of the motor system, specifically the dorsal premotor cortex, reduces metacognitive ability when performing a perceptual discrimination task (Fleming et al., 2014). In addition, Allen et al. (2016) report the results of an interoceptive priming manipulation where autonomic arousal modulates subjective confidence on a motion-discrimination task. Thus, it is has been suggested that movement parameters proprioceptive and interoceptive states may also serve as a useful cue for the inference of confidence in our own decision-making.

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https://doi.org/10.1016/j.concog.2017.11.005
Received 31 May 2017; Received in revised form 3 November 2017; Accepted 13 November 2017

Indeed, previous research has shown that the speed at which a participant makes a forced choice decision is correlated with their confidence, with faster reaction times associated with more confident decisions (Fleming, Weil, Nagy, Dolan, & Rees, 2010). Moreover, subjects are able to infer the subjective confidence of another person simply by the observation of their actions (Patel, Fleming, & Kilner, 2012), with faster movements rated as more confident and vice versa. This is reliant on the motor system as subjects with movement disorders have difficulty inferring the confidence of others moving at speeds very different from their own (Macerollo, Bose, Ricciardi, Edwards, & Kilner, 2015), and disrupting activity in the motor system reduces healthy individuals sensitivity to infer confidence from the kinematics of others (Palmer, Bunday, Davare, & Kilner, 2016).

These findings suggest that an individual may in part infer their confidence in their decisions from their own movement parameters. Here, we tested this hypothesis using a behavioural priming task to alter movement speed, while participants performed a perceptual contrast discrimination task. We recorded the speed at which the participant made their decisions. After each trial of the perceptual decision task, we asked the participant to rate their confidence in their performance, and calculated their metacognitive ability, as a measure of the relationship between their confidence and accuracy.

2. Method

2.1. Participants

Forty-eight healthy participants with normal or corrected-to-normal vision were recruited (31 female, 17 male), with a mean age of 27 (range 18–53, median 24). Forty-four reported being right-handed, four reported being left-handed. The experiment was fully explained to participants, apart from the aim of the project and the true aim of the priming task, which were not disclosed until debriefing to prevent bias. The experiment was approved by the University College London Ethics Review Board. Informed written consent was obtained from all participants and procedures were conducted in accordance with the Declaration of Helsinki.

2.2. Equipment

Participants were seated at a table, 60 cm in front of a Dell laptop computer, and responded using the standard QWERTY keyboard, a marble and three touch-sensitive containers (Fig. 1). Stimulus display and response collection were controlled by MATLAB 7.8.0 (Mathworks Inc., MA, USA) using the Cogent 2000 toolbox (http://vislab.ucl.ac.uk/cogent.php).

2.3. Stimuli and procedure

The experiment was carried out at the Institute of Neurology, University College London. All participants were tested individually, in the presence of the experimenter. Participants completed two blocks of a metacognition task described below (50 trials per block), followed by a movement speed prime (50 trials), a third block of the metacognition task, a second movement speed prime, and finally a fourth block of the metacognition task (Fig. 2a). The first block of the metacognition task was used as a practice session and was not included in the analyses.

2.3.1. Metacognition task

The metacognition task was a perceptual contrast discrimination task used in previous studies (Fleming et al., 2010; Patel et al., 2012). The stimuli were comprised of two images shown in quick succession on the laptop computer screen. Each image comprised a circular clock-face with six Gabor gratings (circular patches of light and dark bars) arranged around a central fixation point (Fig. 2b). The background was uniform grey, with a luminance of 3.66 cd/m^2.

In one of the two images, all the Gabor gratings were set to the same contrast, that is, a 'baseline' Gabor grating. In the other image, one of the Gabor gratings was set to a higher contrast than the other five baseline gratings, causing it to appear as a 'pop-out'. Pop-out gratings were drawn from a stimulus set that varied in contrast between 23 and 80% in increments of 3%. The pop-out Gabor

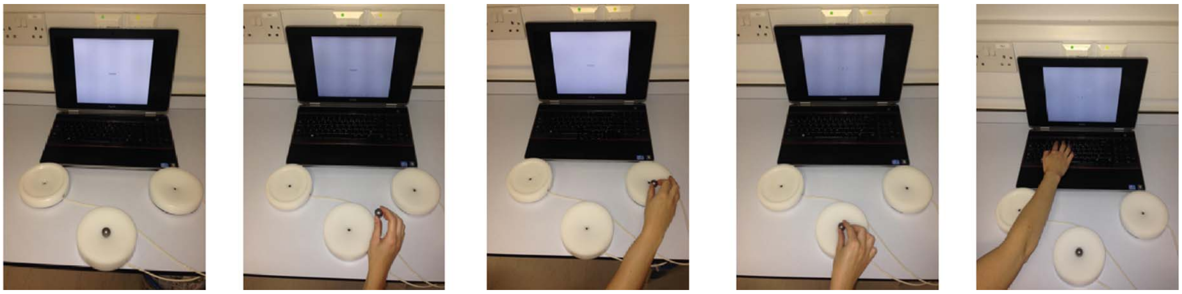

Fig. 1. Experimental setup (photo). Participants moved the marble from the central homepad container to the rightmost container if they believed the pop-out Gabor was present in the first interval, or the leftmost container if they believed the pop-out Gabor was present in the second interval. They then returned the marble to the homepad container. They were then prompted by the computer to enter the value between one and 99 that represented their relative confidence in their decision using the numbers of the keyboard of the laptop.

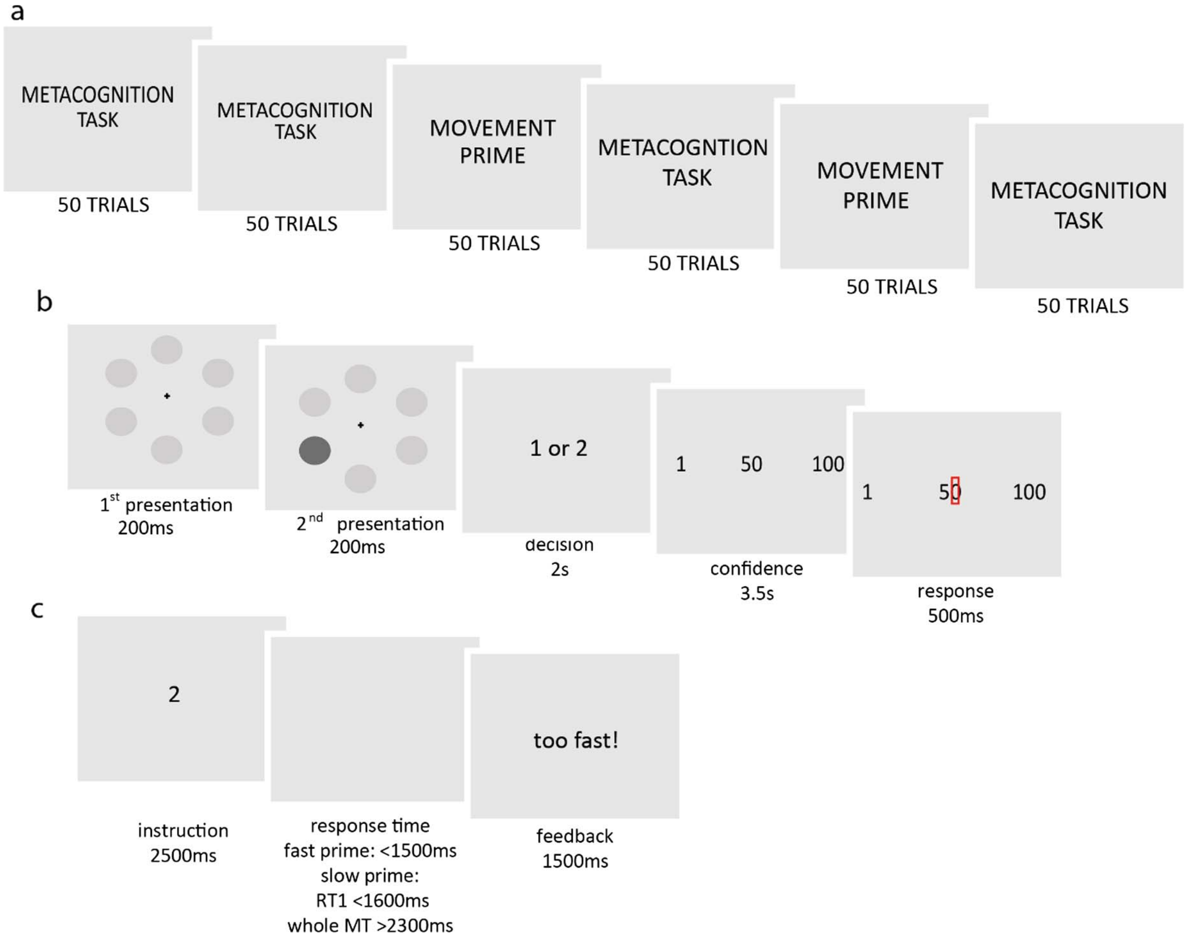

Fig. 2. Experimental procedure schematics: (a) the experiment included four blocks of the metacognition task (50 trials each) and two blocks of the movement prime (50 trials each). All participants completed all six elements. (b) Metacognition Task: participants completed a two-alternative forced-choice task that required two judgements per trial: a perceptual response followed by an estimate of relative confidence in their decision. The perceptual response indicated whether the first or second temporal interval contained the higher-contrast (pop-out) Gabor patch (represented here by a darker circle), which could appear at any one of six locations around a central fixation point. Pop out Gabor contrast was continually adjusted with the use of a staircase procedure to maintain ~70% performance. Confidence ratings were made using a one-to-99 scale, with participants encouraged to use the whole scale from one = low relative confidence to 99 = relative high confidence. The red frame in the rightmost panel indicates the choice made in the metacognitive task. (c) Movement Prime Task: participants were prompted to move the marble from the homepad to either of two containers marked 1 and 2, by the appearance of the number on the screen. They were then given feedback by the computer on their movement speed. The slow prime was designed to slow their movement speed, i.e. the time taken for the entire movement (MT) had to be above 300 ms. The reaction time to begin the movement (i.e. remove the marble from the homepad) (RT1) had to be less than 1600 ms, to ensure that subjects moved slowly and not merely responded slowly. The fast prime was designed to increase their movement speed, i.e. under 1500 ms. Participants then returned the marble to the homepad container before proceeding to the next trial.

grating would appear at random in either the first or second image and at a random spatial position orientated around a central fixation point.

After viewing both images, participants were prompted to make a decision as to which image (first or second) contained the pop-out grating by the appearance of the message “1 or 2” on the screen. Participants made their response by moving a marble from the ‘homepad’, positioned centrally on the table, to one of two containers, marked “1” and “2”. The container marked “1” was always located on the right of the homepad, and “2” on the left. After indicating their decision, participants returned the marble to the homepad. A red square framed their selection on the screen and participants were then prompted to indicate their confidence in their decision by typing a number between 1 and 99. A lower value indicated low confidence and a higher value indicated high confidence.

No feedback was given to participants about the actual accuracy of their decision. Reaction times were recorded from participants while they indicated their decision on the contrast discrimination task, allowing us to operationalise movement speed as the time between the marble being removed from the homepad and placed in a response container.

The contrast of the pop-out Gabor grating was varied throughout the experiment using a two-up, one-down staircase procedure to keep accuracy consistent (Fleming et al., 2014; Patel et al., 2012). The staircase operated such that after two consecutive correct decisions the contrast was decreased by one increment, whereas after one incorrect decision the contrast was increased by one increment. A correct response would thus be made on approximately 70% of trials, ensuring that the analysis of movement speed and confidence was not affected by performance. In addition to movement speed and confidence rating, we also recorded accuracy (correct or incorrect response) and signal strength (pop-out Gabor grating contrast strength) on each trial.

2.3.2. Movement prime

During this task, participants were prompted to move the marble from the homepad to either of the two containers marked “1” and “2”, and then return it to the homepad. The desired location was instructed on a trial by trial basis, by the appearance of a 1 or 2 on the screen. On completing the movement, participants were given visual feedback on the screen about their movement speed (“just right”/“too slow”/“too fast”) (Fig. 2c). Movement speed was calculated from the same reaction time parameters as those used in the metacognition task. The fast prime was designed to increase movement speed above natural average parameters, while the slow prime was designed to decrease movement speed below natural parameters.

In the fast prime task, the goal was for participants to remove the marble from the homepad container and move it to the indicated container as fast as possible. A message of “just right” appeared on the screen if the time it took to complete the task was less than 1500 ms. If the time between the marble being removed from the homepad container and being placed in another container was greater than 1500 ms, a message of “two slow” appeared. In the slow prime task, participants were required to complete the movement of the marble from the homepad container to the indicated container in over 2300 ms. If they accomplished this, a message of “just right” appeared on the screen. If their movement speed was less than 2300 ms, a message of “too fast” was presented. To prevent participants simply delaying the onset of the movement, a message of “start time too slow” was presented if the participant did not remove the marble from the homepad container in under 1600 ms. The order in which participants completed the movement prime task (fast or slow first) was counterbalanced.

2.4. Analyses

As the first block of the metacognition task was used as a practice session, the analyses presented here were conducted on blocks two through four. All trials with a recorded movement time of zero were removed from analyses. Greenhouse-Geisser was used to correct for violated sphericity and a more stringent alpha criterion of p = .01 was used to correct for multiple comparisons, where required.

2.4.1. Analysis 1: Relationship between movement speed and confidence

We conducted a bivariate correlation analysis of confidence and movement speed at baseline (second block of the metacognition task). Movement speeds and confidence ratings were mean-corrected and then ranked by movement speed from fastest to slowest. These values were then divided into ten equal sized bins in order of increasing magnitude. Each bin was then averaged to produce ten mean values for confidence and ten mean values for movement speed. A significant negative relationship would replicate previous findings of an inverse interdependence (Baranski & Petrusic, 1998; Fleming et al., 2010; Patel et al., 2012), whereby higher confidence is associated with faster movement.

2.4.2. Analysis 2: Effect of movement prime on movement speed

An analysis of variance (ANOVA) was used to determine if the movement primes had worked. That is, was there was a significant effect of movement prime on movement time, in the expected direction. In other words, had the fast prime made participants move faster and had the slow prime made participants move slower?

2.4.3. Analysis 3: Effect of movement prime on confidence

An analysis of variance (ANOVA) was used to determine if the movement primes had produced a significant effect on confidence ratings.

2.4.4. Analysis 4: Effect of movement prime on metacognitive accuracy

Firstly, we used a non-parametric measure of metacognitive sensitivity that characterised the probability of being correct for a given level of confidence (Fleming et al., 2010; Patel et al., 2012). Receiver-operating characteristic (ROC) curves were produced for participants’ confidence ratings and accuracy. First, confidence ratings were ranked from lowest to highest and organised into seven bins. Subsequently, hi = p(confidence = I | correct) and fi = p(confidence = I | incorrect) was calculated for each bin, I, whereby “hi” indicates a correct perceptual response (i.e. hit) and “fi” indicates an incorrect response (i.e. false alarm). These probabilities were then transformed into cumulative probabilities and plotted against each other to produce the ROC curve. The area underlying the ROC curve (A_{ROC}) was calculated by the sum of the area between the ROC curve and the area underlying the area of the half-square triangle below the major diagonal:

$$A_{\mathrm{ROC}} = 0.25 \sum_{k=1}^{0} \left[(h_{k+1} - f_k)^2 - (h_k - f_{k+1})^2\right] \Big| + 0.5$$

Thus, the area below the major diagonal in an individual’s ROC curve is a measure of their ability to link confidence to perceptual performance (*A*ROC), in other words, their metacognitive accuracy. Analysis of variance (ANOVA) was used to determine if the movement primes had produced a significant effect on metacognitive accuracy.

Secondly, analysis of variance (ANOVA) and nonparametric permutation were used to determine if there was an interaction effect

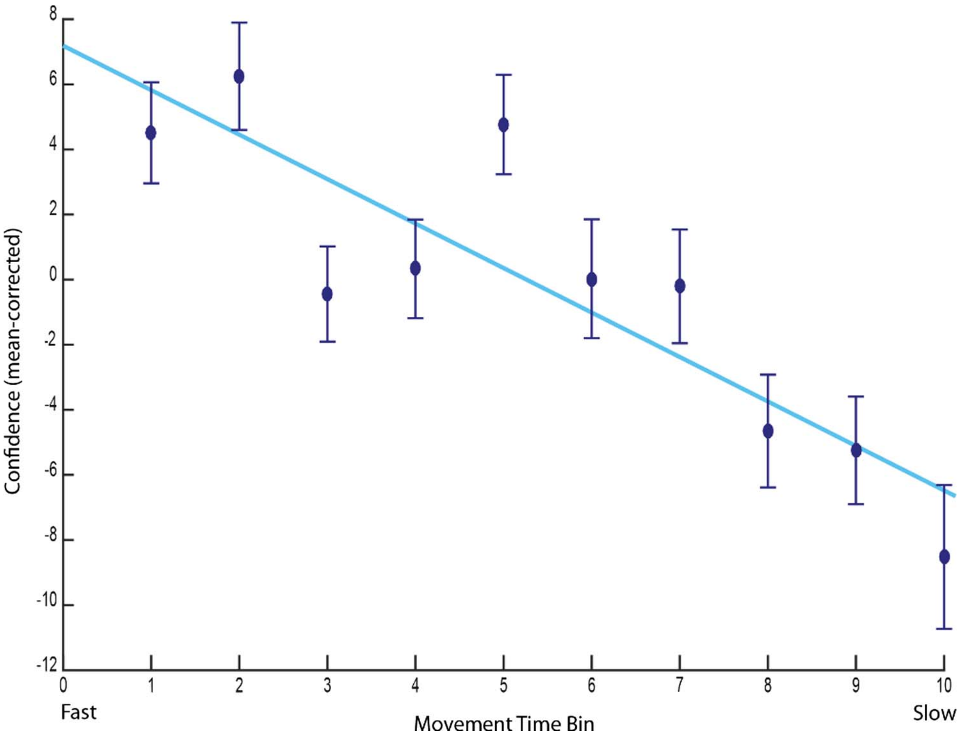

Fig. 3. Average ranked mean-corrected confidence ratings over trials for each subject (n = 48) plotted against average mean-corrected movement time, given in milliseconds. Bivariate correlation analysis revealed a significant negative correlation ($r^2 = -0.870$, $p = .001$). Error bars reflect the standard error of the mean.

between correct and incorrect responses and movement primes on confidence.

3. Results

3.1. Analysis 1: Relationship between movement speed and confidence

A bivariate correlation analysis revealed a significant negative correlation between confidence and movement speed [$r^2 = -0.870, p = .001$, df = 47], before the application of any movement prime tasks (Fig. 3). This replicates previous findings of a negative relationship between confidence and movement speed (Baranski & Petrusic, 1998; Fleming et al., 2010; Patel et al., 2012).

3.2. Analysis 2: Effect of movement prime on movement speed

A one-way repeated-measures ANOVA with three levels (baseline, fast, slow) revealed a significant effect of condition on movement speed [$F(1.62,76.11) = 8.720$, $p = .001$, $\eta p^2 = 0.156$].

Pairwise comparisons revealed significantly faster movement speeds after the fast prime (mean = 706.394, SD = 145.070) compared to baseline measures (mean = 745.460, SD = 165.241) [$t(47) = 3.161, p = .002, d = 0.469$] and slower movement speeds after the slow prime (mean = 776.829, SD = 203.351) compared to after the fast prime [$t(47) = 3.948$, $p < .001$, $d = 0.638$] (Fig. 4a). The difference in movement speed after the slow prime relative to baseline measures was not significant [$t(47) = 1.597$, $p = .117$, $d = -0.239$]. The difference between movement speeds post fast prime and post slow prime was confirmed to be significantly different with a nonparametric sign test ($p < .001$). One large outlying data-point (> 500 ms) can be seen in the Slow condition (Fig. 4a). Removing this participant's data from the analysis revealed the same result, with a main effect of condition [$F(2,92) = 13.542$, $p < .001$, $\eta p^2 = 0.227$], driven by significant differences between baseline and fast conditions [p = .007] and fast and slow conditions [$p < .001$].

3.3. Analysis 3: Effect of movement prime on confidence

A one-way repeated-measures ANOVA with three levels (baseline, fast, slow) revealed no significant main effect of condition on confidence [$F(1.79,84.32) = 0.070$, $p = .916$, $\eta p^2 = 0.001$] (Fig. 4b). One large outlying data-point (> 15) can be seen in the Slow condition (Fig. 4b). Removing this participant's data from the analysis revealed the same result, with no significant main effect of condition [$F(1,46) = 0.057$, $p = .812$, $\eta p^2 = 0.001$].

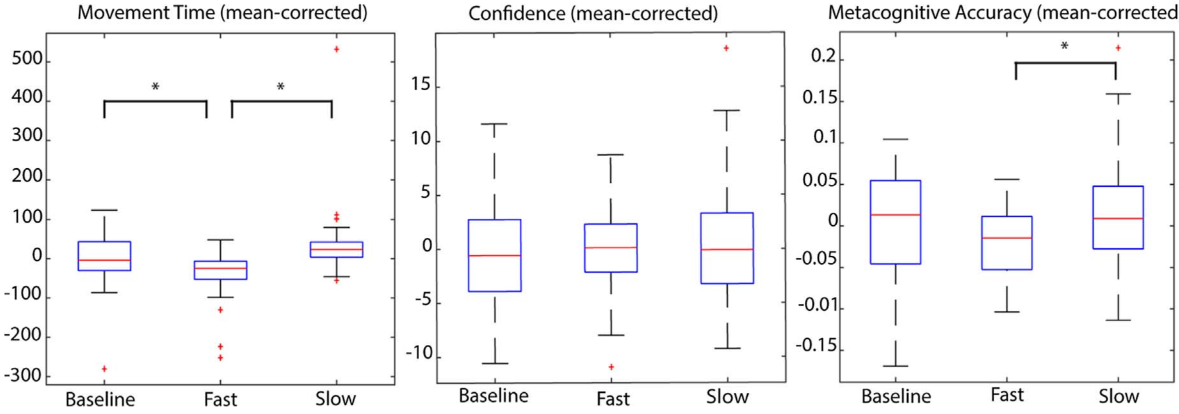

Fig. 4. Average mean-corrected movement time (panel a), confidence (panel b) and metacognitive accuracy (panel c) for all subjects (n = 48) at baseline, and after fast and slow primes ($^{*}p < .05$, two-tailed). A significant decrease in movement time was observed after the fast prime, and significant increase after the slow prime. A significant increase in metacognitive accuracy was observed after the slow prime. Error bars reflect the standard error of the mean.

3.4. Analysis 4: Effect of movement prime on metacognitive accuracy

A one-way repeated-measures ANOVA with three levels (baseline, fast, slow) revealed no significant main effect of condition on [$F(1.56,73.50) = 2.389$, $p = .111$, $\eta p^2 = 0.048$] on A_{ROC}. Specifically looking at the difference in metacognitive accuracy between the two primed conditions revealed significantly higher A_{ROC} after the slow prime (mean = 0.756, SD = 0.080) than after the fast prime (mean = 0.725, SD = 0.089) [$t(47) = 2.659$, $p = .011$, $d = 0.385$) (Fig. 4c). Neither of these values was significantly different to baseline (mean = 0.747, SD = 0.105) (Baseline vs Slow [$t(47) = 0.534$, $p = .596$, $d = -0.077$], Baseline vs Fast [$t(47) = 1.611$, $p = .114$, $d = 0.239$]). One large outlying data-point (> 0.2) can be seen in the Slow condition (Fig. 4c). Removing this participant's data from the analysis revealed the same result, with no main effect of condition [$F(1.637,75.298) = 2.296$, $p = .117$, $\eta p^2 = 0.048$, Greenhouse-Geisser corrected].

As A_{ROC} has previously been found to be influenced by both Type-I accuracy/d′ and criterion (Maniscalco & Lau, 2012; Fleming & Lau, 2014), Spearman's correlation analyses were conducted to confirm that changes observed in A_{ROC} were not the result of conditional changes in these measures. There was no significant correlation between A_{ROC} and d′ [$r^s = 0.175$, p = .234] or A_{ROC} and criterion [$r^s = -0.077$, p = .602] after the fast prime or between A_{ROC} and d′ [$r^s = -0.123$, p = .407] or between A_{ROC} and criterion [$r^s = 0.189$. p = .199] after the slow prime (see Supplementary Fig. 1). (See also Supplementary Fig. 2 for subject wise Type-II ROC curves for each condition).

As we had found a significant difference in metacognitive accuracy between the primed conditions in the absence of significant changes in confidence, we investigated whether changes in confidence were dependent on participant's accuracy. To this end, a two-way repeated-measures ANOVA was conducted with a factor of response (2 levels, correct or incorrect) and a factor of condition (3 levels: baseline, fast prime, slow prime) was performed. This revealed a significant main effect of response, with significantly higher confidence on correct trials than incorrect trials [$F(1,47) = 169.559$, $p < .001$, $\eta p^2 = 0.783$]. There was no significant main effect of condition [$F(1,47) = 0.823$, $p = .369$, $\eta p^2 = 0.005$]. There was a significant interaction between the two [$F(1.99, 93.66) = 5.487$, $p = .006$, $\eta p^2 = 0.188$].

To investigate the location of the interaction effect, we removed the main effect of response by mean-correcting the confidence data. Confidence ratings for correct and incorrect responses were mean-corrected separately. As a result, the main effect of response was no longer significant [$F(1,47) = 0.823$, $p = .269$, $\eta p^2 = 0.021$] but the results of the main effect of condition and interaction effect remained identical [$F(1,47) = 0.823$, $p = .369$; $F(1.99,93.66) = 5.487$, $p = .006$, $\eta p^2 = 0.188$, respectively]. Pairwise comparisons revealed significantly higher confidence for incorrect responses (mean = 1.519, SD = 5.068) than correct responses (mean = −1.523, SD = 4.455) after a fast prime [$p = .002$, $d = 0.469$] (Fig. 5). All other comparisons were insignificant after correcting for multiple comparisons.

Furthermore, we tested whether this interaction effect was also significant using non-parametric analysis. To this end, we ran a permutation test on the interaction. We simulated 10,000 permutations to determine the distribution of values for the interaction of interest. In each simulation, the average confidence ratings for each of the four conditions were randomly assigned to the four conditions: Fast Prime correct, Slow Prime incorrect, Fast Prime Incorrect, Slow Prime correct. This was performed for each participant independently. The average interaction value was then calculated across participants as above. Once this had been repeated 10,000 times, the distribution of the interaction terms could be plotted, and the point of the true interaction value on this distribution was calculated. This test also revealed a significant interaction effect (less than 0.1% of the data had permutations at a higher value than the true value, i.e. $p < .001$). In other words, this interaction effect occurred by chance in less than 0.1% of circumstances, indicating this to be a robust effect.

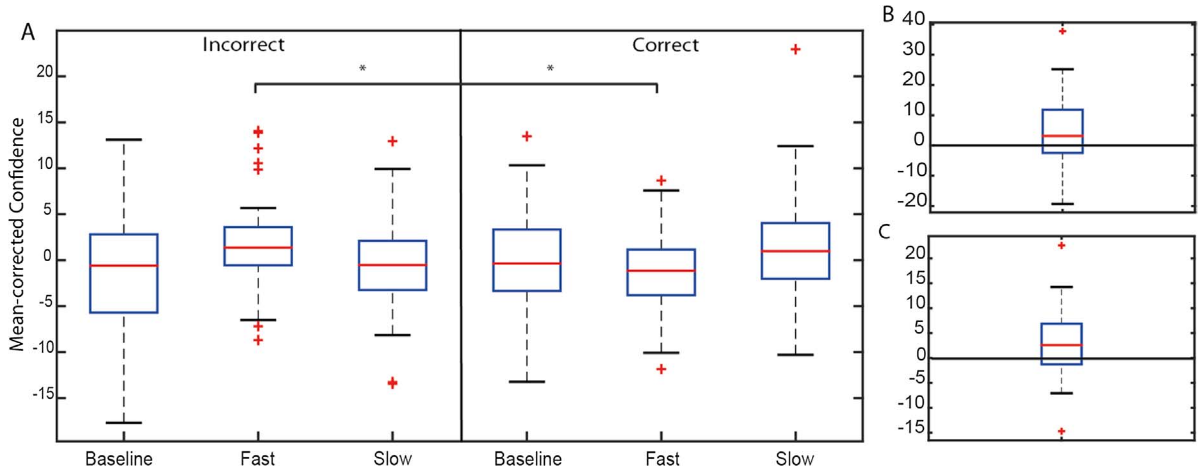

Fig. 5. Panel A: Average mean-corrected confidence for all subjects at baseline, and after the fast and slow primes. Confidence on incorrect and correct trials were mean-corrected separately and are thus plotted separately. After the fast prime, participants reported significantly higher confidence on incorrect trials than correct trials (p = .002, two-tailed, Bonferroni-corrected). Panel B shows the interaction term for (incorrect responses after a fast prime – incorrect responses after a slow prime – correct responses after a fast prime – correct responses after a fast prime). Panel C shows the difference between correct and incorrect responses for the fast prime.

4. Discussion

Here we tested the hypothesis that altering participants' movement speed will disrupt their ability to form accurate confidence judgements of their performance. The results supported this hypothesis by indicating that after being primed to move faster than they would naturally, participants report higher confidence in their incorrect decisions than their correct ones. Overall, metacognitive accuracy was significantly higher when participants were slowed than when they were quickened. These findings suggest that the metacogntive ability to match confidence to accuracy relies on a veridical signal from the motor system.

These data are consistent with previous findings on the role of the motor system in judgements of perceptual confidence. We replicated the finding that the speed at which an individual makes a forced choice decision is correlated with their confidence, with faster reaction times associated with more confident decisions (Fleming et al., 2010). Consistent with the finding that disrupting activity in the motor system reduces an individual's ability to form accurate judgements of confidence (Fleming et al., 2014) and to infer confidence from the kinematics of others (Palmer et al., 2016), here we find that altering an individual's kinematics behaviourally reduces their ability to infer their own confidence.

The absence of a significant direct effect of movement time on confidence in the presence of a relationship between confidence, accuracy and movement, suggests that the relationship between metacognition and movement is not a simple linear one. In this study, moving faster does not increase confidence and moving slower does not decrease confidence directly. However, moving faster when you are incorrect raises your confidence above and beyond what it is following a correct response. It is important to note that feedback on performance was not provided to participants in the research reported here. Thus, the only information participants had to use in their judgement about their confidence was the decision making process itself, including the movement made to indicate their response. It is possible that if participants possess an internal model of their decision making, including the movement made to indicate that decision, modifying movement parameters may disrupt the learnt relationship between how movement time relates to confidence. In effect, participants are no longer able to successfully 'read out' their confidence from their movement time. As a result, their metacognitive ability can no longer be predicted.

The results presented here point towards a role of kinematics in higher-order cognitive functions, such as the metacognitive monitoring of performance. Previous research had shown that cognition has a top-down influence on an individual's motor behaviour, i.e. that we move faster when we're feeling more confident (Audley, 1960; Baranski & Petrusic, 1998; Henmon, 1911; Johnson, 1939; Patel et al., 2012; Volkmann, 1934), but the results of the current research also suggests that we may need an accurate and veridical representation of our motor behaviour in order to form accurate and veridical cognitive judgements. This supports a more 'closed-loop' view of action and cognition, whereby there are bottom-up influences on cognition from the body, in addition to the more closely studied top-down cogntive influences on behaviour. As such, the present findings hold implications for traditional views of cognition, as operating on a distinct plane from the motor system.

While the results of the current research do suggest a trial by trial correspondence between confidence and accuracy that is influenced by ascending information from the effector about the movement speed used to indicate the decision, the present design does not allow us to comment on whether continued processing of this information takes place. According to decision-locus models of metacognition confidence is solely based on evidence available at the point of the judgement (Kiani & Shadlen, 2009; Vickers, 1979). Alternatively, according to postdecisional-locus models, metacognitive evidence continues to be accumulated after the decision has been made (Pleskac & Busemeyer, 2010). Evidence from transcranial magnetic stimulation (TMS) indicated that stimulation applied after the decision affected confidence judgements and does support the latter hypothesis (Fleming et al., 2014). The time course of this effect, however, is not known. Further research might investigate for what length of time after movement modulation metacognitive disruption is seen.

In this study we demonstrated a causal role of the motor system in metacognition, specifically, that how an individual moves when they make a decision impacts their ability to relate their feelings of confidence to their performance. This finding suggests that humans obtain information about their confidence levels by monitoring their movement kinematics and that these inferences can be manipulated by changing how subjects move. It would be interesting for future research to investigate the role that organic changes in movement speed, such as that seen in Parkinson's disease, play in metacognitive ability and estimates of subjective states, such as confidence. This research suggests that highlights the need for researchers should to consider the inclusion of kinematic information in subsequent models of metacognition. One such model is presented by Fleming and Daw (2017), which accounts for action in self-evaluation judgements proposes that individuals form confidence estimates by applying an analogous computation to their own actions.

Funding

This work was supported by a PhD studentship awarded to E.R.P. from the Economic and Social Research Council (ESRC) and the Medical Research Council (MRC). A.K. was supported by a 'European Research Council Starting Investigator Award' [ERC-2012-STG GA313755].

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.concog.2017.11.005.

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