Abstract

Confidence leak (i.e., confidence serial dependence) is a phenomenon where confidence from a previous trial predicts confidence in a current trial independent of current choice or accuracy. Confidence leak has been shown to robustly occur across various cognitive domains and tasks. However, it remains unclear what factors, if any, modulate the strength of the confidence serial dependence. Here we investigate whether switching the motor response in a perceptual decision-making task influences the strength of the confidence leak effect. Subjects indicated the orientation of a Gabor patch using their left or right hand, with the response hand being randomly cued on each trial. We found that switching the response substantially weakened the confidence leak effect. We further replicated this finding in a second experiment in which left-hand responses were given using a keyboard and right-hand responses were given with a mouse. In both experiments, we also found that confidence leak was weaker whenever the left hand was used in the previous trial, suggesting that lack of motor fluency reduces the strength of confidence serial dependence. These results demonstrate that switching the motor response weakens serial dependencies and imply that the action required to make a choice can impact one's metacognitive evaluations.

Word count: 199

1. Introduction

A confidence judgment about a current stimulus can be predicted from a previous confidence judgment about a different stimulus. This confidence serial dependence phenomenon is known as “confidence leak” (Rahnev et al., 2015; Mei et al., 2023). Confidence leak is thought to occur across virtually any task and domain but nonetheless remains severely underexplored. In fact, it has been explicitly investigated in only five papers (Mueller & Weidemann, 2008; Rahnev et al., 2015; Kantner et al., 2019; Aguilar-Lleyda et al., 2021; Mei et al., 2023) and one conference abstract (Ng et al., 2021).

The earliest investigation of confidence leak appears to be in a paper focused on providing evidence for decision noise in perceptual decision-making (Mueller & Weidemann, 2008). Mueller & Weidemann showed that subjects had a tendency to repeat the same confidence judgment in consecutive trials, which shows the existence of noise in the confidence criterion placement. The first paper specifically devoted to confidence serial dependence showed that confidence leaks across different perceptual tasks and different ways of indicating confidence, thus ruling out simple motor confounds (Rahnev et al., 2015). Confidence leak was subsequently demonstrated within recognition memory and was even shown to occur across tasks from different domains (in this case memory and perception) (Kantner et al., 2019). Similarly, Mei et al. (2023) showed that a classifier trained on confidence serial dependence in one domain can predict confidence serial dependence in different domains. Finally, confidence leak has been shown to occur even when the previous trial did not require an explicit confidence judgment (Aguilar-Lleyda et al., 2021).

As the brief review above shows, while confidence leak has been established as a ubiquitous and robust phenomenon, it is still unclear whether the strength of the effect can be modulated. One particular source of modulation could be the motor action used to make a response. Indeed, both first-order choices and confidence judgments in simple psychophysical tasks are mediated by the action required to indicate the decision (Prinz, 1990; Creem-Regehr & Kunz, 2010; Lepora & Pezzulo, 2015; Selen et al., 2012; Burk et al., 2014; Fleming et al., 2015; Gajdos et al., 2019; Kubanek et al., 2024). Some modulations of first-order choices include the motor effort (Burk et al., 2014) or the motor cost (Gajdos et al., 2019) of the action associated with the decision, where perceptual decisions associated with less costly actions are preferred. Confidence judgments have also been shown to depend on the perceptual-motor mapping of representations (Faivre et al., 2020; Fleming et al., 2015; Gajdos et al., 2019). For example, TMS perturbations of premotor cortical regions influence confidence without affecting signal discrimination abilities (Fleming et al., 2015). Overall, motor actions have been shown to robustly affect confidence judgments, but whether or not they also modulate confidence serial dependence remains unknown.

To test whether the perceptual-motor link also mediates the strength of the confidence leak effect, we conducted two experiments where subjects completed an orientation discrimination task. Critically, on different trials, subjects were randomly cued to respond using either the left or right hand. We found that switching the motor response significantly decreased the strength of confidence serial dependence. However, we also found that using the left hand on the previous trial was associated with weaker confidence leak, suggesting an underlying mechanism that goes beyond recently formed perceptual-motor mappings. These results suggest that different motor aspects of making a decision influence the amount of confidence leak observed in future judgments.

2. Methods

2.1. Subjects

Forty-five subjects participated in Experiment 1 and 51 subjects participated in Experiment 2. A total of four subjects were excluded (three for Experiment 1 and one for Experiment 2) for using a single confidence rating in over 90% of the trials, because such extreme responses make estimates of confidence serial dependence unstable. All had normal or corrected-to-normal vision and signed a consent form prior to participation.

2.2. Stimuli and procedure

In both experiments, subjects completed a 2-choice orientation discrimination task. Each trial began with a 500-ms fixations screen, followed by a Gabor patch presented for 200 ms in the center of the screen (Figure 1). After the stimulus disappeared subjects were required to indicate the correct Gabor patch orientation (counterclockwise vs. clockwise from vertical). After they made a choice, subjects gave a confidence rating on a 4-point scale where 1 is the lowest and 4 is the highest confidence rating. Both decisions were untimed. The Gabor patches (size = 4° of visual angle) were oriented 45° clockwise or counterclockwise relative to vertical, with a spatial frequency of 1.5 cycles per degree. The Gabor patches were presented in two contrast conditions (low vs. high). Both Gabor orientations appeared with equal probability throughout the experiment.

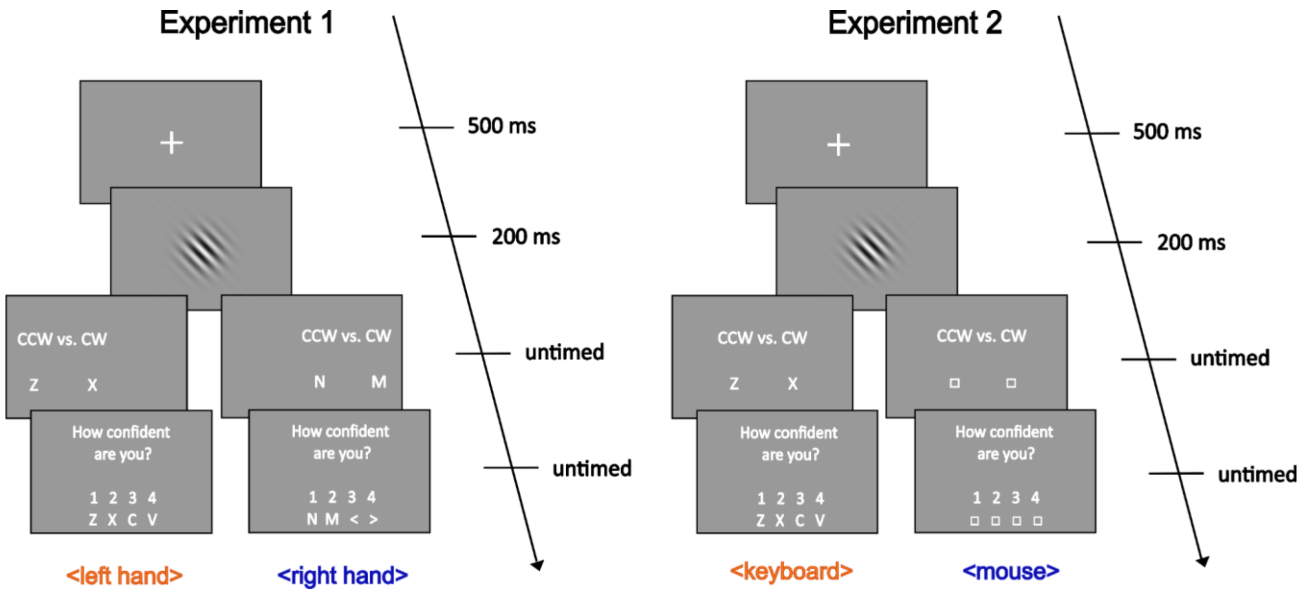

Figure 1. An example trial. A 500-ms fixation cross was followed by a 200-ms Gabor patch oriented either clockwise (CW) or counterclockwise (CCW). Subjects indicated the tilt of the Gabor patch and gave confidence on a 4-point scale. In Experiment 1, the text that served as the decision prompt was positioned either on the left or right side of the screen and indicated which hand the response should be made with. In Experiment 2, left-hand responses were made with the keyboard, whereas right-hand responses were made with a mouse. In both experiments, the confidence judgment was made with the same hand as the perceptual decision.

Both experiments consisted of a total of 1000 trials separated into 4 runs, where each run consisted of 5 blocks of 50 trials each. Subjects were given a 15-second breaks between blocks and unlimited breaks between runs.

The training phase consisted of three blocks in total. The first block consisted of 20 trials where the Gabor contrast was fixed to 0.4. The other two training blocks consisted of 15 trials each with Gabor contrast set to 0.18 and 0.14, respectively. Decreasing contrast at this rate made the task harder with each training block. During the training session, subjects were given trial-by-trial feedback about the accuracy of their response. The training blocks were followed by two staircase blocks used to estimate the optimal contrast level for each subject. The first staircase block was a 2-down-1-up with a step size of .01 and a total of 14 reversals. The second staircase was a 3-down-1-up and had the same parameters. The two contrast levels in the actual experiment (low vs. high) were set separately for each subject by either dividing the mean value across the two staircases by 1.2 (resulting in a low contrast value) or multiplying it by 1.2 (resulting in a high contrast value). The average values of the low and high contrasts were 8.1% (SD = 0.09) and 11% (SD = 0.09) for Experiment 1, and 5.8% (SD = 0.01) and 8.4% (SD = 0.01) for Experiment 2, respectively.

2.2.1 Experiment 1: Keyboard only

In Experiment 1, subjects were instructed to make their perceptual and confidence decisions with either the left or right hand using a keyboard. Whenever the left hand was prompted, responses were given by pressing “Z” for a counterclockwise-oriented Gabor and “X” for a clockwise-oriented Gabor, and confidence ratings were given via “Z”, “X”, “C”, and “V”, where “Z” indicated the lowest confidence and “V” indicated to the highest confidence. Similarly, when the right hand was prompted, responses were given by pressing “N” for a counterclockwise-oriented Gabor and “M” for a clockwise-oriented Gabor. Confidence ratings were given via the “N”, “M”, “<” and “>” keys, where “N” indicated the lowest confidence and “>” indicated the highest confidence.

2.2.2 Experiment 2: Keyboard and mouse

In Experiment 2, subjects were instructed to make their perceptual and confidence decisions with either a keyboard (using their left hand) or a mouse (using their right hand). The left-hand keyboard responses were the same as in Experiment 1: subjects gave their responses by pressing “Z” for a counterclockwise-oriented Gabor and “X” for a clockwise-oriented Gabor and gave their confidence ratings with keys “Z” through “V”. Subjects gave mouse responses by checking boxes on the screen to first give their perceptual judgment and subsequently indicate their confidence rating on a 4-point scale.

2.3. Apparatus

Stimuli in both experiments were generated using Psychophysics Toolbox in MATLAB (MathWorks, Natick, MA) and were presented on a gray background (6.0 cd/m2). The task was ran on an iMac monitor (19 inch monitor size, 1680 × 1050 pixel resolution, 60 Hz refresh rate). Subjects sat 60 cm away from the monitor.

2.4. Analyses

We first excluded trials with response times over 3000 ms in either the perceptual or confidence judgment (2.2% and 4.6% of trials were excluded in Experiments 1 and 2, respectively). We used repeated measures ANOVAs to assess the effect of current and previous contrast on confidence and task performance. We then employed linear regression to compute both choice and confidence serial dependence by fitting the lagged series (t-1) of trials as a predictor of the regular time series for repeat-hand and switch-hand trials separately. We used paired sample t-tests to compare the beta coefficients for repeat-hand and switch-hand trials. To assess whether hand dominance modulated confidence leak, we assumed that statistically the majority of our subjects would be right-handed since we did not record hand dominance. We used the same analyses for comparing previous left-hand and right-hand responses.

2.5. Data and Code

All data and code are available at https://osf.io/qjwdx/?view_only=d359da48583d4b8da6fc26b311740c2a.

3. Results

Our goal was to investigate how motor aspects of making a decision influence confidence serial dependence. To do so, we manipulated the hand with which subjects gave their motor response. We then compared confidence serial dependence when the same hand was used in consecutive trials vs. when a hand switch occurred.

3.1. Manipulation checks

We first confirmed that subjects performed better for high compared to low Gabor contrast. This was indeed the case for both experiments (Expt 1: high contrast = 82% correct; low contrast = 69% correct ($t(41) = 19.9$, $p = 1.06 \times 10^{-22}$, Cohen's $d = 3.07$; Expt 2: high contrast = 80% correct; low contrast = 67% correct ($t(49) = 27.8$, $p = 1.01 \times 10^{-31}$, Cohen's $d = 3.94$). Similarly, higher Gabor contrast led to higher confidence ratings (Expt 1: $t(41) = 9.29$, $p = 1.21 \times 10^{-11}$, Cohen's $d = 1.43$; Expt 2: $t(49) = 10.48$, $p = 4.10 \times 10^{-14}$, Cohen's $d = 1.48$).

We further confirmed the existence of robust confidence serial dependence (Expt 1: average $\beta = .3$, $p = 3.44 \times 10^{-18}$, Cohen's $d = 2.3$; Expt 2: average $\beta = .3$, $p = 1.33 \times 10^{-21}$, Cohen's $d = 2.3$). Similar to Rahnev et al., (2015), experimentally manipulating confidence on the previous trial by varying the contrast level of Gabor patches had a causal effect on confidence on the current trial (Expt 1: $F(1, 41) = 50.61$, $p = 1.03 \times 10^{-8}$, $\eta_p^2 = .55$; Expt 2: $F(1, 49) = 52.89$, $p = 2.46 \times 10^{-9}$, $\eta_p^2 = .51$).

3.2. Confidence leak strength decreases for switch-hand trials

Having established the existence of robust confidence leak, we then turned to the main analyses where we compared confidence leak between repeat-hand and swich-hand trials. In Experiment 1, we found significant confidence leak for both repeat-hand (average β = .33, t(41) = 15.9, p = 3.76 x 10^{-19}, Cohen's *d* = 2.43) and switch-hand trials (average β = .28, t(41) = 13.2, p = 2.56 x 10^{-16}, Cohen's d = 2.03). Critically, the strength (β value) of confidence serial dependence was higher in the repeat-hand condition (t(41) = 4.9, p = .00002, Cohen's *d* = .75; Figure 2). These results were replicated in Experiment 2. Specifically, confidence leak was significant for both repeat-hand (average β = .34, t(49) = 18.6, p = 7.32 x 10^{-24}, Cohen's *d* = 2.62) and switch-hand trials (average β = .25, t(49) = 10.2, p = 9.25 x 10^{-14}, Cohen's *d* = 1.44), but was crucially higher for repeat-hand trials (t(49) = 3.92, p = .0002, Cohen's *d* = .55). These results show that switching the motor response weakens confidence serial dependence.

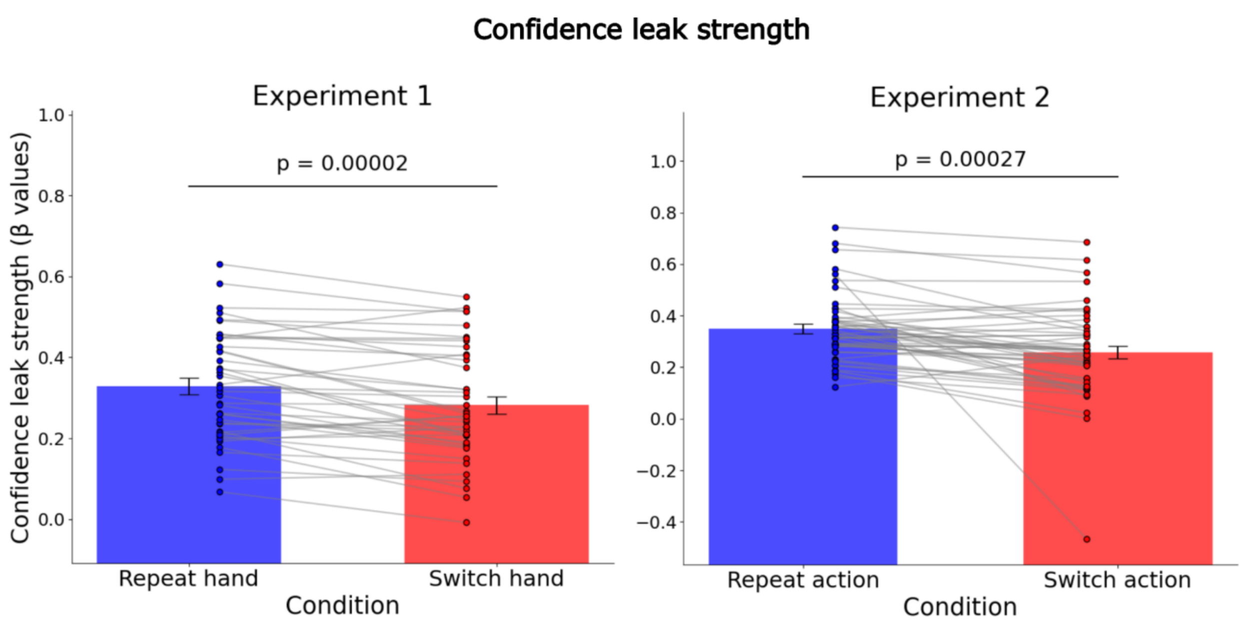

Figure 2. Confidence leak strength decreases for switch-hand trials. Confidence serial dependence was significantly lower for switch-hand compared to repeat-hand trials. Confidence

serial dependence strength was quantified as the beta value in a lag-1 linear regression. Lines and small circles show individual subject data. Error bars equal 1 S.E.M.

We ran the same analyses for the main perceptual decision (left vs. right Gabor patch tilt). Regular choice serial dependence was significant for repeat (average $\beta = .12$, $t(49) = 7.03$, $p = 1.47 \times 10^{-8}$, Cohen's $d = 1.08$) and switch (average $\beta = .08$, $t(49) = 5.04$, $p = 9.71 \times 10^{-6}$, Cohen's $d = .77$) trials. Just like with confidence leak, repeating the motor response significantly increased the strength of serial dependence ($t(41) = 3.5$, $p = .001$, Cohen's $d = .54$). In Experiment 2, the same was true for repeat (average $\beta = .1$, $t(49) = 7.85$, $p = 3.20 \times 10\text{-}^{10}$, Cohen's $d = 1.11$) and switch (average $\beta = .06$, $t(49) = 4.91$, $p = 1.04 \times 10^{-5}$, Cohen's d = .69) trials. Once again, the difference between the two conditions was significant ($t(49) = 4.89$, $p = .00001$, Cohen's $d = .69$). This indicates a strong motor modulation of a much weaker type of serial dependence than confidence leak.

3.3. Confidence leak strength is lower when the prior response is made with the left hand

As reviewed earlier, confidence judgments are known to be modulated by the motor effort of the response (Gajdos et al., 2019; Faivre et al., 2020). Correspondingly, one may expect that motor effort would mediate confidence leak as well. In Experiment 1, this type of effect should lead to lower confidence leak when subjects used the left hand on the previous trial because that is the non-dominant hand for about 90% of people (Raymond et al., 1996). Indeed, we found that confidence serial dependence was significantly weaker when using the left hand in a previous trial ($t(41) = 3.7$, $p = .0006$, Cohen's $d = .57$) (Figure 3).

In contrast to Experiment 1, the design in Experiment 2 is more complex, which allows for different predictions. On one hand, one may postulate that motor costs are higher for left-hand responses (since the left hand is usually non-dominant) and therefore predict higher confidence leak when the right hand was used on the previous trial. On the other hand, one may postulate that motor costs are higher for right-hand responses (since people used their right hand to give responses via the mouse, and making responses with a mouse requires more complex motor action) and therefore predict higher confidence leak when the right hand was used on the previous trial. To find out which prediction is correct, we performed the same analyses for Experiment 2 as in Experiment 1. We found weaker confidence leak when using the left hand on the previous trial ($t(49) = 3.9$, $p = .0003$, Cohen's $d = .55$), which is consistent with the expected effects of hand-dominance but contrary to the expected effects of increased motor complexity due to using the mouse. Together, these results demonstrate that motor effort can modulate confidence leak strength, and suggest that the hand dominance effect has a stronger influence than the means by which the response is given.

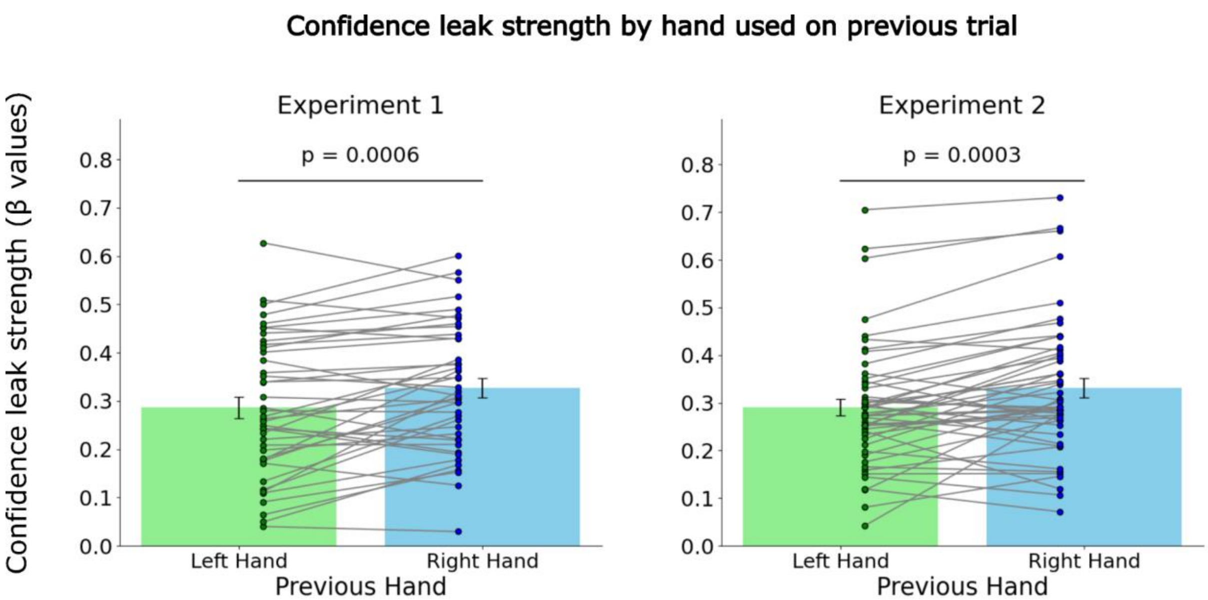

Figure 3. Confidence leak is weaker for left-handed previous responses. We found overall weaker confidence serial dependence for the left hand in a previous trial. The effect was present in both experiments irrespective of the type of motor response. Error bars equal 1 S.E.M.

4. Discussion

Confidence leak is a temporal judgment bias where confidence in a current trial can be predicted based on confidence from the preceding trial. It has been shown to occur across various tasks (Rahnev et al., 2015) and cognitive domains (Mei et al., 2023; Kantner et al., 2019; Aguilar-Lleyda et al., 2021). However, it is unclear whether the strength of this bias can be artificially reduced. We created a perceptual task where subjects were required to discriminate between two Gabor orientations by unpredictably switching the motor response. We then collected confidence ratings on a trial-by-trial basis. We found that confidence leak decreases with switching the hand used to give the response. Moreover, we showed that confidence leak was weaker whenever the left hand was used in the previous trial. These results suggest that the degree of confidence leak can be modulated by the motor aspects of the task.

The fact that switching the motor response decreased the strength of confidence leak is in line with prior research on the motor influences on confidence itself. Indeed, as discussed in the Introduction, multiple studies have demonstrated that our motor actions can influence confidence judgments (Fleming et al., 2015; Gajdos et al., 2019). Specifically, Fleming et al. showed that TMS stimulation of motor areas associated with the unchosen response reduced confidence in the correctness of the perceptual decision. Further, confidence has been found to be significantly higher in trials with EMG-recorded subthreshold motor activity (Gajdos et al., 2019). Together, these results support the general decision-making argument that decisional variables are passed onto the motor system before a decision is made (Selen et al., 2012; Kubanek & Kaplan, 2012). However, our results build on this understanding of perception-action modulations by showing that motor changes can behaviorally disrupt decisions in the metacognitive domain.

We found that hand dominance modulated the strength of serial dependence such that using the left hand in a previous trial reduced confidence leak. In other words, confidence judgments made with the left hand are less able to influence subsequent confidence judgments (regardless of which hand is used in the subsequent judgment). One possible interpretation of this finding is that using one's non-dominant hand to indicate a decision incurs motor cost. In turn, this motor cost interferes with the encoding of the confidence judgment in an active state that is able to influence subsequent decisions. Such mechanism builds on previous findings that have typically focused on the fact that motor cost can influence the perceptual decisions made on the current trial (Marcos et al., 2015; Hagura et al., 2017). Our findings suggest that higher motor cost not only influences the current perceptual decision but also interferes with the process of using the decision (and its associated confidence) in subsequent decision-making.

There are important implications of confidence leak modulation. In general, confidence leak can be cast as a type of metacognitive noise (Shekhar & Rahnev, 2021a; 2021b; 2024). That is, confidence leak induces noise in the confidence criteria by pulling them up or down based on the confidence in the previous trial (Rahnev et al., 2015). Therefore, the fact that increasing the motor costs can reduce confidence leak suggests that it should also reduce metacognitive noise. Thus, our findings propose promising ways for future experiments to develop designs that minimize metacognitive noise.

Our results raise the question as to whether other manipulations can also modulate confidence leak. Prior research has demonstrated that confidence ratings themselves can be influenced by a variety of factors such as arousal level (Allen et al., 2016; Hauser et al., 2017), brain stimulation (Rounis et al., 2010; Fetsch et al., 2014; Shekhar & Rahnev, 2018; Xue et al., 2023), evidence volatility (Zylberger et al., 2016; Boldt et al., 2017), and stimulus uncertainty

(Kiani et al., 2014; Zylberger et al., 2014; de Gardelle & Mamassian, 2015; Spence et al., 2018). It is reasonable to hypothesize that some of these factors would affect not only the confidence on the current trial but also the strength with which the confidence on the current trial influences confidence on the subsequent trial. We expect that future studies will demonstrate additional influence on confidence leak beyond the motor costs examined in the current study.

In conclusion, we showed that confidence serial dependence can be modulated by switching the motor response in a perceptual task. In addition, we found weaker confidence leak when the non-dominant hand was used in the previous trial. Together, these results suggest that motor responses, and motor fluency in particular, influence the confidence judgments people make when evaluating perceptual decisions.

Declarations

Funding

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Conflicts of interest

The authors have no competing interests to declare that are relevant to the content of this article.

Ethics approval

The study was approved by the Institutional Review Board of the Georgia Institute of Technology.

Consent to participate

All participants provided written consent to participate in the study.

Consent for publication

All participants signed informed consent to publish their data.

Availability of data and materials

The data and materials for all experiments are available at https://osf.io/qjwdx/?view_only=d359da48583d4b8da6fc26b311740c2a and none of the experiments were preregistered.

Code availability

Not applicable.

Authors' contributions

Dobromir Rahnev conceived, programmed and conducted the experiment; Michaela Bocheva conceived, ran and interpreted the analyses; Michaela Bocheva and Dobromir Rahnev wrote the manuscript.

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