How Does Action Influence Metacognition? An Exploration Based on Cognitive Models and Neural Mechanisms

Authors: Cheng Xiaorong, Qiu Shiming, Fixed precipitous peak, Fan Zhao, Fan Zhao

Date: 2024-12-11T00:00:00+00:00

Abstract

Action and metacognition constitute important components of cognitive processing. Metacognition reflects an individual's representation, monitoring, and regulation of cognitive processes, whereas action serves as a crucial means of outputting internal cognitive processing, particularly decision-related information. Research indicates that various aspects of action (such as response speed, response intensity, response sequence, response conflict, and action observation) all influence metacognition. From a cognitive modeling perspective, post-decision models of metacognition are well-suited for explaining the relevant experimental evidence regarding how action influences metacognition. Such models posit that information used for metacognitive evaluation (metacognitive evidence) differs from yet is related to information used for perceptual judgment (perceptual evidence), and they respectively emphasize hierarchical processing, Bayesian computation, confidence enhancement, and other aspects. From a neural mechanism perspective, action and perceptual information may be integrated through a brain network centered on the frontoparietal cortex, relying on electrophysiological mechanisms such as beta oscillations and alpha suppression, thereby forming metacognition under attentional regulation. Future research could further explore the boundary conditions under which action alters metacognition, the true meaning of confidence reports, and metacognitive performance in special populations, among other topics.

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How Does Action Influence Metacognition? — An Exploration Based on Cognitive Models and Neural Mechanisms

CHENG Xiaorong#, **QIU Shiming#**, DING Xianfeng, FAN Zhao
(Key Laboratory of Adolescent Cyberpsychology and Behavior (CCNU), Ministry of Education; Key Laboratory of Human Development and Mental Health of Hubei Province; School of Psychology, Central China Normal University (CCNU), Wuhan 430079, China)

# These authors contributed equally to this work.

Abstract

Action and metacognition are crucial components of cognitive processing. Metacognition reflects an individual's ability to represent, monitor, and regulate cognitive processes, while action serves as a vital means of outputting internal cognitive processing, particularly decision-making information. Research has demonstrated that various aspects of action—such as response speed, response intensity, response sequence, response conflict, and action observation—all influence metacognition. From the perspective of cognitive models, post-decision models of metacognition are well-suited to explaining the experimental evidence regarding how action influences metacognition. These models propose that the information used for metacognitive evaluation (metacognitive evidence) differs from but is related to that used for perceptual judgment (perceptual evidence), focusing respectively on hierarchical processing, Bayesian computation, and confidence enhancement. From the perspective of neural mechanisms, action and perceptual information may be integrated through brain networks centered on the frontal cortex, relying on electrophysiological mechanisms such as β oscillations and α inhibition, with metacognition shaped under attentional regulation. Future research could further explore the boundary conditions under which actions alter metacognition, the true meaning of confidence, and the metacognitive performance of special populations.

Keywords: action, metacognition, perceptual judgment, confidence evaluation, cognitive and neural mechanisms
Classification code: B842

Humanity's ability to understand and transform the world presupposes a stable and efficient cognitive processing system. Action and metacognition are two indispensable components within this cognitive processing architecture. As cognition about cognition (MacNeil et al., 2024), metacognition manifests an individual's capacity to represent, monitor, and control mental functions (Boldt & Gilbert, 2022; Fleming, 2024; Rausch et al., 2023), enabling people to evaluate the quality of their choices, actions, and performance, and to adjust current behavior and optimize future decisions even in the absence of external feedback. Effective metacognition is reflected in reasonable second-order evaluations of one's own first-order decisions, particularly through sufficiently accurate confidence judgments. Post-decision confidence reports are widely regarded as a key metric for measuring metacognition. In high-stakes domains such as financial investment (Dhingra & Yadav, 2024), medical diagnosis (Al-Maghrabi et al., 2024), courtroom trials (Lebensfeld & Smalarz, 2024), and political decision-making (Milshtein et al., 2024), as well as in social interactions, possessing accurate confidence judgments about one's own decisions and correctly understanding others' decision confidence carry significant adaptive value.

Traditional cognitive psychology has primarily focused on "action-free" pure cognitive activities. However, researchers have increasingly begun to emphasize the role of action representation and processing in cognition. Action serves as a means of outputting internally processed information. In the narrow sense, action refers to explicit, measurable muscular responses, including subthreshold activation (Gajdos et al., 2019), action preparation (Wokke et al., 2020), and action execution (Pereira et al., 2020). Extensive recent literature supports that action observation and action execution share partially overlapping neural mechanisms (Cardellicchio et al., 2020). Consequently, the broad definition of action can be extended to include motor cortex activation induced by observing others' actions (Charles et al., 2020) or imagining one's own actions (Chye et al., 2022), as well as interference with central motor activity using devices such as transcranial current/magnetic stimulation (TCS/TMS). Regardless of definition, action represents a crucial means of outputting internal cognitive processing, particularly decision-making information, providing vital clues for revealing the interaction between the cognitive "black box" and the external world.

This paper focuses on how action influences metacognition in perceptual tasks. Early perceptual models held that confidence judgments were primarily based on the quality or intensity of sensory processing (Pezzetta et al., 2022), thus not anticipating that actions occurring after perceptual processing would affect confidence in perceptual decisions. However, with the deepening of motor cognition research, investigators have discovered perceptual decision signals within motor centers, indicating a close connection between action and confidence judgment (Wokke et al., 2020). Recently, a growing body of research has demonstrated that action can directly influence confidence judgments—that is, alter metacognition (Faivre et al., 2020; Fleming et al., 2015; Mazancieux et al., 2023; Palser et al., 2018; Sanchez et al., 2024; Siedlecka et al., 2021; Wokke et al., 2020). These findings reveal that metacognition is not "action-free" but instead heavily relies on the activation and participation of the action system.

Research on how action influences metacognition can not only advance metacognitive theory but also help expand frontiers in action and cognition (Chye et al., 2022), perception and decision-making (Mamassian & de Gardelle, 2022), embodied cognition (Wokke et al., 2020), and evidence integration and accumulation (Mazancieux et al., 2023). This paper systematically reviews experimental evidence of action's influence on metacognition, examines relevant cognitive models and neural mechanisms, and attempts to clarify various debates surrounding this influence (centered on the degree of dependence, modes of association, and organizational structure between perceptual and metacognitive evidence), concluding with several prospects for future research.

2 Experimental Evidence of Action Altering Metacognition

The classic research paradigm for perceptual metacognition involves first making a perceptual response, then reporting metacognition—that is, reporting confidence in the response (Gajdos et al., 2019). Consequently, perceptual judgments are termed type I tasks, while confidence judgments are termed type II tasks (Maniscalco & Lau, 2012). Beyond raw confidence ratings, several metrics for measuring metacognitive ability have been derived by computing the relationship between perceptual judgments and confidence ratings (see reviews by Fleming & Lau, 2014; Rausch et al., 2023). These primarily include: (1) metacognitive bias, which refers to participants exhibiting overall overconfidence or underconfidence despite equivalent perceptual performance, also known as type II bias; (2) metacognitive sensitivity, which reflects the ability to correctly discriminate between correct and incorrect judgments, also termed metacognitive accuracy or type II sensitivity/discriminability, with common metrics including the area under the type II ROC curve (AUROC2) (Fleming & Lau, 2014) and meta-d' (Maniscalco & Lau, 2012); (3) metacognitive efficiency, which refers to the level of metacognitive sensitivity given a specific objective task performance (d'), typically measured as meta-d'/d', also known as Mratio (Fleming & Lau, 2014); and (4) confidence-accuracy regression slope, with some studies using regression analysis to predict perceptual response accuracy from confidence and experimental conditions, employing the regression slope as an index of metacognitive ability (Faivre et al., 2020).

Previous research held that confidence judgments rely entirely on perceptual evidence (see review by Yeung & Summerfield, 2012). However, an increasing number of studies have demonstrated a dissociation between objective perceptual performance and subjective confidence judgments (Di Luzio et al., 2022). For instance, Wokke et al. (2017) found that perceptual decisions utilize all visual information, whereas metacognitive decisions rely only on partial information. This dissociation is also manifested in the "matched-performance/different-confidence" (MPDC) phenomenon (Maniscalco et al., 2020; Rollwage et al., 2020), where confidence judgments show significant differences across experimental conditions despite equivalent perceptual task performance, possibly because response actions provide additional evidence for confidence judgments. More recently, Siedlecka et al. (2021) compared metacognitive performance with and without action responses, finding that confidence judgments were higher when action responses were present, regardless of response accuracy. Additionally, Charles et al. (2020) demonstrated that participants reported higher confidence and exhibited greater metacognitive bias under voluntary action conditions compared to passive action conditions. These findings collectively indicate that first-order judgments and metacognitive judgments may be based on different information sources. Confidence judgments depend not only on sensory-perceptual information but may also be influenced by other factors within the perception-action processing pathway. The following sections explore how different aspects of action influence metacognition.

2.1 Interference with Motor Cortex Affects Metacognition

Studies have shown that interfering with motor cortex regions related to action can affect metacognition, providing direct evidence that action alters metacognition. The prefrontal cortex (PFC) is a core brain region closely associated with metacognition (Geurts et al., 2022; Lapate et al., 2020). Applying continuous theta burst stimulation (cTBS) to this region can significantly enhance metacognitive efficiency (Hobot et al., 2023). Furthermore, the PFC has direct neural connections with the premotor cortex. In a study by Fleming et al. (2015), participants judged whether a grating stimulus appeared on the left or right side of a screen while receiving single-pulse transcranial magnetic stimulation (TMS) to the premotor cortex. The results showed that TMS had no significant effect on perceptual judgments but exhibited a congruency effect on confidence ratings: confidence scores were significantly higher when the stimulated brain region was congruent with the response hand (contralateral) compared to when it was incongruent (ipsilateral). However, replicating this experiment on the primary motor cortex (M1) yielded no similar effects (Palmer et al., 2016). Additionally, research has found that when the motor system is disrupted, not only do confidence judgments change, but subjective perceptual awareness judgments are also affected (Hobot et al., 2020). These findings suggest that higher-level motor representations in the premotor cortex, which connect to the PFC, play an important role in perceptual confidence, whereas the primary motor cortex is unrelated to metacognition. In summary, both direct interference with the PFC and indirect interference via the motor cortex can alter metacognition, with the latter likely influencing confidence judgments through higher-level representations in the premotor cortex.

2.2 Response Speed Influences Metacognition

Research has found that action response speed is closely related to metacognition. For example, in a task requiring participants to make forced-choice judgments about grating luminance by moving a marble (left or right), marble movement speed positively correlated with confidence—the faster the speed, the higher the confidence (Patel et al., 2012). Other studies have also shown that perceptual response time negatively correlates with confidence—shorter response times correspond to higher confidence (Filevich et al., 2020; Overhoff et al., 2022; Rahnev et al., 2020). Furthermore, Palser et al. (2018) used a priming paradigm and found that when response speed was primed to exceed natural levels, it disrupted participants' confidence judgments about their own performance, manifesting as enhanced confidence in error trials. These findings indicate that feedback information from response effectors participates in metacognitive processing. Some scholars have proposed that the phenomenon of faster responses yielding higher confidence may stem from response fluency (Brouillet et al., 2023), where smoother and easier responses produce stronger confidence. However, recent research has revealed that the effect of response fluency is conditional, whereas the precision of response actions has a more direct impact on metacognition, even overshadowing the role of response fluency in some cases (Sanchez et al., 2024). For instance, Sanchez et al. (2024) demonstrated that action precision directly reflects monitoring level—the higher the precision, the greater the monitoring and confidence. This result suggests that metacognition is predominantly influenced by action precision rather than response fluency.

2.3 Action Intensity Influences Metacognition

What intensity of action can influence metacognition? Recent research indicates that even subthreshold behavioral responses can affect metacognition (Gajdos et al., 2019). In Gajdos et al.'s study, participants judged grating orientation using left and right thumb presses while electromyography (EMG) signals from the flexor pollicis brevis muscle were recorded. EMG activity preceding the keypress reflected motor preparation processes and, since no overt action had yet occurred, was termed subthreshold action. Analyses revealed that trials with subthreshold motor activation before the keypress showed higher confidence ratings than trials without such activation, while grating orientation judgments remained unaffected. This suggests that motor preparation or related latent variables can influence confidence, consistent with the view that metacognition integrates information from perception-action pathways. Beyond subthreshold actions, suprathreshold action intensity perceived by individuals also affects metacognition. Turner et al. (2021) investigated how different levels of physical effort influence metacognition in perceptual tasks. In their experiment, participants judged the luminance of left and right squares by applying different grip force intensities (20%, 40%, or 60% of maximum grip force) and subsequently rated their confidence. The results showed that greater grip force intensity led to higher confidence ratings. A similar phenomenon has been observed in studies using perceptual awareness assessment as a type II task (Qiu et al., 2024), where higher grip force intensity resulted in higher subjective perceptual awareness ratings.

2.4 Response Sequence Influences Metacognition

Confidence judgments typically occur after perceptual responses and may therefore be influenced by preceding actions. Previous research has manipulated the relative sequence of perceptual decisions and confidence judgments in experiments to investigate the effect of response sequence on metacognition. For example, Siedlecka et al. (2016) required participants to form words from presented letters and judge whether target words matched the words they had formed. By manipulating the timing of confidence judgments, they found that confidence judgments made after perceptual responses were more accurate than those made before perceptual responses. More recently, Wokke et al. (2020) further examined how action response information and the timing of confidence judgments affect metacognition. Participants needed to judge the color of the majority of dots in a moving dot array. Confidence judgments were made under three conditions: after the color judgment (with actual action), before the color judgment but after the color judgment cue (without actual action but with action preparation), and before the judgment cue (with neither action nor action preparation). As the confidence judgment was moved earlier in the sequence, available action information progressively decreased. The results showed that metacognitive efficiency based on confidence judgments after perceptual responses was significantly higher than when action information was absent.

2.5 Action Conflict Information Influences Metacognition

The influence of action conflict information on metacognition manifests primarily in two aspects: first, sensorimotor conflict, where motor signals and somatosensory signals are incongruent; and second, conflict between response cues and actual responses.

Regarding sensorimotor conflict, Faivre et al. (2020) established two conditions: action-sensation synchrony and a 500 ms delay (the sensorimotor conflict condition). After maintaining the synchronous or conflict state for 10 seconds, participants completed temporal order judgments for sounds and confidence assessments. The results showed no significant difference in temporal order judgments between the two conditions, but sensorimotor conflict significantly reduced confidence assessments. Regarding response cue conflict, Siedlecka et al. (2020) required participants to determine which of two pictures (left or right) contained more dots, with congruent (e.g., left-right arrows) or incongruent (e.g., up-down arrows) response cues presented after the stimulus. The findings indicated that congruent cues enhanced subsequent confidence assessments. This same cue congruency effect has also been observed in studies using perceptual awareness as a metacognitive indicator (Siedlecka et al., 2019). However, Sanchez et al. (2023) found that when response cues appeared before the stimulus, the results contradicted the aforementioned studies: incongruent response cues (e.g., a leftward arrow indicating a left-hand response) paired with actual responses (e.g., using the right hand) led to higher confidence assessments. The researchers propose that this may arise because spatial representations during response preparation are monitored and used for confidence judgments. When response cues conflict with actual responses, enhanced control over spatial representations and inhibition of irrelevant representations are required, and this additional control increases confidence assessments.

2.6 Observing Others' Actions Alters Metacognition

In addition to one's own actions altering metacognition, observing others' actions also influences metacognition. Patel et al. (2012) had participants complete a perceptual forced-choice task and make metacognitive judgments, then watch videos of others performing the same task and infer the others' confidence. The results showed that the faster the observed response speed in the videos, the higher the participants' inferred confidence for the other person. Moreover, this inference depended on the participants' own task performance: when participants' response speeds were slower than those of the individuals in the videos, they tended to infer that the others had higher confidence than themselves. This indicates that participants based their inferences of others' confidence on their own performance.

Not only does observing and comparing others' response speeds alter metacognition, but direct interference with the motor system also affects metacognitive judgments based on observing others' actions. Palmer et al. (2016) employed a similar action observation paradigm and found that applying continuous theta burst stimulation to the primary motor cortex (M1) could alter participants' inferences about others' confidence. This result is inconsistent with the aforementioned study where TMS interference with M1 did not change metacognition (Fleming et al., 2015). However, the paradigms differed between these studies: the former focused on observing others' actions, while the latter examined one's own actions. This suggests that the effects of observing others' actions versus performing one's own actions on metacognition may involve different neural mechanisms, warranting further investigation.

3 Cognitive and Neural Mechanisms of Action Altering Metacognition

The aforementioned empirical studies demonstrate that various aspects of action processing can significantly influence metacognition, yet the underlying cognitive and neural mechanisms remain unclear and lack a unified consensus. The following sections explore the cognitive and neural mechanisms of action altering metacognition by integrating existing metacognitive models.

3.1 Cognitive Models of Action Altering Metacognition

An increasing number of contemporary theories posit a distinction between perceptual evidence and metacognitive evidence, with action influencing metacognition in many contexts. How should we construct cognitive models of action altering metacognition? This question essentially addresses the relationship between the evidence underlying perceptual judgments and metacognitive judgments—the degree of dependence, modes of association, and organizational structure between these two types of evidence. Specifically, are perceptual and metacognitive evidence independent? If not, how are they associated? And what structural and organizational principles govern how associated evidence functions in both types of judgments? Early research primarily revolved around two extreme hypotheses. The single-channel model posits that perceptual and metacognitive decisions rely on the same sensory evidence, sharing an identical source (Shekhar & Rahnev, 2021). However, this model cannot explain the dissociation between perceptual and metacognitive phenomena nor support the influence of action on metacognition. In contrast, the dual-channel model emphasizes that perceptual and metacognitive decisions depend on completely different sensory evidence or arise from independent parallel processing, though certain evidence or processes may simultaneously influence both decisions to some extent (Maniscalco & Lau, 2016). Although the dual-channel model can partially explain the separation between perception and metacognition, its assumption of a complete dissociation between the two evidence types is inconsistent with empirical findings. Current theories tend to favor the view that evidence underlying perceptual and metacognitive decisions is neither fully independent nor completely identical, but rather possesses some degree of association. Nevertheless, the specific nature of this association and the mechanisms of evidence accumulation remain under investigation (Fleming & Daw, 2017; Pleskac & Busemeyer, 2010). Some theories propose that confidence forms during the perceptual decision process—so-called pre-decisional models (Lee et al., 2023). However, more research indicates that action information can only influence metacognition when confidence evaluation occurs after perceptual decisions (Wokke et al., 2020). Consequently, current experimental evidence increasingly converges on supporting post-decisional models, where sensorimotor information provided by action influences metacognition after (rather than before) perceptual decisions. Even after perceptual decisions are completed, confidence evidence continues to accumulate dynamically and persistently affects metacognition (Desender et al., 2021; Mazancieux et al., 2023). The following are the main post-decisional models.

3.1.1 Hierarchical Model The hierarchical model (Lau & Rosenthal, 2011) explains how action alters metacognition and how perceptual and metacognitive performance can dissociate by modifying the processing mode of metacognition rather than introducing independent sources of metacognitive evidence. This model suggests that perceptual and metacognitive decisions may be based on the same evidence, but the source or quality of the evidence differs, with more important distinctions emerging gradually in how the evidence is processed and organized. According to the hierarchical model, first, the processing mode is hierarchical—different processing of the same evidence is organized hierarchically, with new processing continuously introducing new noise and rewriting the hierarchical structure of evidence. Second, the processing mode is sequential—early processing generates objective decisions, while later processing inherits evidence from early processing and evaluates it to produce subjective decisions (Maniscalco & Lau, 2016). A representative example of the hierarchical model is the two-stage dynamic signal detection theory (Pleskac & Busemeyer, 2010). This theory emphasizes the dynamic nature of decision-making, proposing that both perception and metacognition rely solely on sensory information about the stimulus. Only after the perceptual decision does information continue to be processed and evidence continues to accumulate—the longer the interval between stimulus presentation and decision, the more sensory evidence accumulates and the more noise is introduced, or the more easily the quality of sensory information changes, thereby creating differences between first-order (perceptual) and second-order (metacognitive) decisions. Action information occurring after stimulus presentation but before metacognitive judgment participates dynamically in metacognitive decision-making, potentially serving as metacognitive evidence to improve decision quality or as noise that interferes with metacognitive decisions.

Maniscalco and Lau (2016) specifically compared three models (single-channel, dual-channel, and hierarchical). Through data simulation and model complexity comparisons, they found that the hierarchical model better explained the dissociation between perceptual and metacognitive performance. However, Shekhar and Rahnev (2024) discovered that post-decisional models represented by the two-stage dynamic signal detection theory were not the best fit for experimental data. Shekhar and Rahnev (2024) proposed a new model—the logWEV model. This model comprises two components: the first builds upon their previously proposed LogN model (Shekhar & Rahnev, 2021), which posits that metacognitive noise follows a lognormal distribution that continuously blurs and weakens confidence criteria. The second component proposes that confidence judgments are based on a weighted sum of perceptual evidence and stimulus visibility—the WEV (weighted evidence and visibility) model (Rausch et al., 2020). They argue that this new model, which combines the dual influences of metacognitive noise and stimulus visibility, can explain experimental data better than single post-decisional models. Nevertheless, Shekhar and Rahnev (2024) also note that under certain experimental conditions (such as rapid responses or sustained stimuli), post-decisional processing that includes action response information may still exist. In summary, questions regarding the applicability of hierarchical models and the construction of optimal metacognitive models require further investigation.

3.1.2 Metacognitive Computational Bayesian Model Single-channel, dual-channel, and hierarchical models either emphasize that sources of metacognitive evidence are dependent on perception or that independent sources of metacognitive evidence exist. The metacognitive computational Bayesian model proposed by Fleming and Daw (2017) has two core assumptions: first, metacognition and perception have distinct but coupled sources of evidence, with confidence evidence being highly correlated with perceptual evidence, thus requiring consideration of their covariance during confidence computation (Schulz et al., 2023). Second, self-evaluation of perceptual performance should fully utilize confidence evidence and one's own behavior, with metacognitive processing described through Bayesian computation. This model posits that self-generated responses convey an individual's internal state (Fleming, 2024) and, together with other confidence evidence, form confidence assessments. Responses are not only an important source for confidence evaluation but also influence metacognitive monitoring and control (Schulz et al., 2023). Consequently, action responses may produce two effects: first, metacognitive assessments after action responses exhibit higher metacognitive sensitivity; second, metacognitive assessments after action responses may lead to lower metacognitive ratings. Both effects have been validated in studies manipulating response sequence (Siedlecka et al., 2016; Wokke et al., 2020). Research has found that when responses precede metacognition, the additional action information helps improve metacognitive efficiency. However, manipulating response sequence not only changes the availability of action information but may also prolong the interval between stimulus and metacognitive evaluation, thereby increasing noise and attenuating signals. Schulz et al. (2023) argue that improvements in metacognitive efficiency more likely stem from increased action information rather than signal attenuation (since signal attenuation would decrease metacognitive efficiency). In summary, while it is known that both action information and signal/noise influence metacognition, how to disentangle their specific contributions to metacognition requires further investigation.

3.1.3 The 'Noise'-'Boost' Trade-off Theory of Confidence Mamassian and de Gardelle (2022) proposed a signal detection theory-based generative model (SDT-based generative model) that borrows architecture from dual-channel models. This model suggests that confidence judgments originate from perceptual decisions and confidence evidence, dividing confidence evidence into two categories: primary confidence evidence (a copy of perceptual evidence and the basis for perceptual decisions) and secondary confidence evidence (additional evidence used for confidence judgments). An ideal confidence observer relies solely on primary evidence, whereas a super-ideal observer relies entirely on secondary evidence. The model posits that confidence computation is governed by a trade-off between confidence noise and confidence boost. Confidence noise reflects inefficiency in confidence computation and reduces confidence sensitivity. Confidence boost refers to post-perceptual information not used for perceptual decisions but utilized for confidence judgments. The trade-off between these two factors determines confidence levels: high boost and low noise yield higher confidence, while low boost and high noise produce lower confidence. In the model, the proportion of ideal versus super-ideal observers is reflected in the confidence boost parameter. Confidence boost may originate from motor signals (Fleming et al., 2015; Wokke et al., 2020), attentional changes (Rahnev & Fleming, 2019), and further information processing after perceptual decisions (Pleskac & Busemeyer, 2010). Thus, this model can similarly explain how motor signals or actions influence confidence processing.

It should be noted that although certain post-decisional models (such as the hierarchical model and the 'noise-boost' trade-off theory) consistently agree that additional confidence evidence exists after perception to influence judgments, these models do not explicitly define the sources of this evidence, which are not limited to action information but may also include factors such as expectations

(Olawole-Scott & Yon, 2023), arousal (Legrand et al., 2021), and motivation (Hoven et al., 2022). While these models do not specifically explain the influence of action information on metacognition, they do provide theoretical support for it. The influence of action information related to perceptual decisions on metacognition reviewed in this paper—including effects of response speed, action intensity, response sequence, action conflict, and action observation on metacognition (see Faivre et al., 2020; Fleming et al., 2015; Mazancieux et al., 2023; Palser et al., 2018; Sanchez et al., 2024; Siedlecka et al., 2021; Wokke et al., 2020)—provides direct experimental evidence for these models.

3.2 Neural Mechanisms of Action Altering Metacognition

Goodale and Milner (1992) first proposed that two neural pathways exist in the brain—the ventral stream and dorsal stream—responsible respectively for visual perception (e.g., object feature recognition) and visually guided action (e.g., grasping objects). Further research has found that in goal-directed behavior, the visual features of targets and related action information are processed separately in these two pathways (Tang et al., 2022). Notably, the ventral and dorsal streams are not completely isolated but exhibit information exchange (Milner, 2017). Giarrocco and Averbeck (2021) discovered that interactive information between ventral and dorsal pathways is integrated via the posterior cingulate and hippocampus before ultimately converging in the prefrontal cortex (PFC) (Milner & Goodale, 1993, 1995). The PFC is precisely a crucial brain region for metacognitive processing. Therefore, perceptual information from the ventral stream and action information from the dorsal stream may be integrated and processed here to form metacognitive judgments, providing a neural foundation for action's influence on metacognition.

Recent fMRI research has precisely localized brain regions related to confidence evaluation, finding that these regions are primarily concentrated in frontoparietal and cingulo-opercular networks, particularly the dorsal anterior cingulate cortex, supplementary motor area, anterior prefrontal cortex, inferior parietal lobe, precuneus, and anterior insula (Qiu et al., 2018; Rouault & Fleming, 2020). One study comparing brain activation with and without confidence evaluation after perceptual decisions found significantly increased activation in the left supplementary motor area, left dorsal anterior cingulate cortex, left frontal operculum, and bilateral precuneus when confidence evaluation was required (Lei et al., 2020). The activation of these regions, including the supplementary motor area, suggests that action information may be involved in metacognitive processes. Although current research on the neural mechanisms of how action influences metacognition is limited, preliminary exploration can proceed from the following aspects.

3.2.1 Functional Specificity of Different Prefrontal Modules Research has explored the functions of different prefrontal modules in metacognition formation. Using TMS, Shekhar and Rahnev (2018) found that applying TMS to the dorsolateral prefrontal cortex (DLPFC) decreased confidence ratings, whereas applying TMS to the anterior prefrontal cortex (aPFC) improved metacognitive ability. Additionally, studies have shown that continuous theta burst stimulation to the left anterior medial prefrontal cortex (aMPFC) can significantly enhance metacognitive efficiency (Hobot et al., 2023). These results indicate functional differences across prefrontal regions: the DLPFC is responsible for reading out sensory evidence, interoceptive signals, and action responses, and transmitting this information to the aPFC, which integrates non-perceptual information to make metacognitive decisions. Therefore, functional differences among prefrontal modules provide a basis for the separation between perception and metacognition and offer a neural foundation for action altering metacognition. Another study combining EEG and fMRI techniques (Pereira et al., 2020) compared metacognitive performance and neural mechanisms when individuals executed actions versus observed others' actions, finding better metacognitive performance during action execution, suggesting that action execution enhances metacognitive performance by accumulating more evidence. The study also found that neural activity correlated with confidence earlier in the action execution condition, and that differences in co-activation between execution and observation conditions appeared early in the anterior insula and later in the aPFC, indicating that after action execution, the anterior insula first detects first-order response motor signals used for error detection and transmits them to the aPFC, where they combine with confidence evidence to form confidence judgments.

3.2.2 Neural Basis for Integration of Action and Internal States Fleming and Daw (2017) argue that action, as additional information, must be integrated with participants' internal states (such as decision and confidence processing variables) to form metacognitive decisions. They propose two potential key brain regions and neural circuits through which action alters metacognition. First, the frontopolar cortex (FPC; Brodmann area 10) may be responsible for integrating action and internal states. The FPC receives multimodal information from higher-level sensory and motor regions in the parietal, frontal, and temporal lobes and integrates this information to support metacognitive decisions (Baird et al., 2013). Second, the dorsomedial prefrontal cortex (dmPFC, encompassing the paracingulate and pre-supplementary motor area) may also participate in integrating action and states. Previous research has found that when participants make rapid keypress responses, the dmPFC shows increased activation when errors occur without external feedback, indicating this region's involvement in error detection (Carter et al., 1998). Additionally, the dmPFC connects with the insula and frontopolar cortex, forming a potential metacognitive evaluation circuit (Baird et al., 2013).

How are action and internal states integrated, or how does action transmit sensory information to form metacognitive decisions? One possible electrophysiological mechanism is the β wave. Research indicates that β oscillations are closely related to sensory and motor processing (Pfurtscheller & Lopes da Silva, 1999). For example, lateralized β wave components in motor areas can predict upcoming actions, demonstrating that β waves are associated with action unfolding (Donner et al., 2009). Furthermore, β oscillations support long-range neural interactions (Siegel et al., 2012) and help maintain current sensorimotor states (Engel & Fries, 2010). Since metacognition requires integrating information about action and internal perceptual states, β waves may serve as a bridge between the two. Wokke et al. (2020) found that when metacognitive judgments occurred after perceptual judgments (i.e., when action information could be processed metacognitively), higher phase synchronization of β waves emerged between motor and prefrontal cortices—indicating that the influence of action information on metacognition is associated with β wave synchronization between motor and prefrontal cortices, providing direct electrophysiological evidence for action information affecting metacognition. In control experiments where metacognitive judgments were not required, this phase synchronization disappeared, further demonstrating the important role of β waves in maintaining sensorimotor states and forming metacognition.

During confidence decision-making, integrating information such as action (Wokke et al., 2020), internal states (including interoception and proprioception) (Fleming, 2024), and visual-temporal cues (Charles et al., 2020) may activate multiple brain regions associated with processing single-dimensional information. Jaeger et al. (2020) found that confidence decision formation is associated with co-activation of three distinct brain region groups, whose activation levels positively correlate with confidence—the stronger the confidence, the more significant the activation. The three groups include: a right fronto-temporo-parietal central region, left temporoparietal region and basal forebrain, and the cerebellum. These brain regions are independent yet widely distributed; they first independently process various types of information relied upon for confidence formation before integrating this information. Among these three groups, the supplementary eye field within the right fronto-temporo-parietal central region is the only area associated with both confidence decisions (Gajdos et al., 2019) and metacognitive efficiency (Fleming & Lau, 2014), potentially playing a key role in integrating action signals and influencing confidence judgments.

3.2.3 Neural Basis of Attentional Inhibition in Action Influencing Metacognition As confidence evidence, action information cannot be overlooked when accumulating with other evidence, making the role of attention crucial. Recent research supports attention's role in confidence evidence accumulation. Sanchez et al. (2023) investigated how action preparation influences confidence judgments. In their experiment, researchers provided response cues before stimulus presentation, indicating which hand participants should use for responding. The results showed that confidence was actually higher when cues were incongruent with actual responses compared to congruent conditions, accompanied by higher P2 amplitudes. P2 amplitude is associated with cognitive control (Xie et al., 2020) and early attentional resource allocation (Ghin et al., 2022). The higher P2 amplitudes in incongruent trials suggest that more attentional resources were allocated to inhibiting the initially mismatched action preparation. This stronger inhibition was integrated into confidence evidence, thereby producing higher confidence.

Furthermore, the influence of action information on metacognitive decisions may also be reflected through α inhibition phenomena. α wave suppression is considered a concrete manifestation of an attentional gate, characterized by suppressing distracting stimuli (Foxe & Snyder, 2011). For example, brain regions processing potentially distracting information show higher α wave power (Foxe et al., 1998). Faivre et al. (2018) studied cross-modal metacognition and found that low confidence was associated with high α wave power, manifesting as α suppression. This may occur because during low confidence, individuals are busy suppressing distracting information and fail to effectively attend to action information from first-order responses (such as action preparation and response time), resulting in low confidence. Therefore, although action information plays an important role in metacognitive decisions, whether it can be attended to may be affected by noise; when noise is high, α suppression comes into play, action information is not attended to, leading to low confidence. Another recent study specifically examined the role of α oscillations in perceptual decision-making (Di Gregorio et al., 2022). They found that fast α wave frequencies before stimulus presentation were associated with correct responses, while slow frequencies were associated with error responses; α wave amplitude was related to confidence. After stimulus presentation, α wave frequency had no effect on accuracy, whereas low α wave amplitude was associated with high confidence assessments and metacognitive sensitivity. Moreover, through TMS modulation, the study found that α modulation before stimulus presentation could only alter response sensitivity, not metacognitive performance, whereas α modulation after stimulus presentation but before confidence judgment (with a perceptual response in between) could only alter metacognitive sensitivity, not response sensitivity. This study not only demonstrates that response and confidence are dissociable but also provides causal evidence for a double dissociation between α wave speed and amplitude in neural mechanisms. Synthesizing these findings, when action information is integrated into metacognitive evidence to form metacognitive judgments, attention primarily operates through inhibition. Inhibition may involve suppressing irrelevant action preparation, thereby increasing confidence, or suppressing irrelevant noise during evidence accumulation, thereby ignoring action information and decreasing confidence.

In summary, we have attempted to outline the neural mechanisms of action altering metacognition at different levels. Synthesizing existing experimental evidence and theoretical explanations, humans likely integrate action information with other evidence to form metacognition through frontocortical-centered brain networks, relying on electrophysiological mechanisms such as β oscillations and α inhibition, with the aid of attentional monitoring. However, current research on the neural mechanisms of action influencing metacognition remains insufficient; although attention's role has been identified, attention has not yet been directly manipulated. Future empirical research is needed to comprehensively reveal the neural mechanisms through which action alters metacognition.

4 Summary and Outlook

In summary, the influence of action on metacognition has been confirmed across numerous studies. Various aspects of action—such as response speed, action intensity, response sequence, and action conflict information—all affect metacognitive performance. Current research on action influencing metacognition is burgeoning, with relevant experimental facts and theoretical explanations urgently requiring further exploration. To further clarify the many debates surrounding how action influences metacognition, particularly regarding the degree of dependence, modes of association, and organizational structure between perceptual and metacognitive evidence, research could be deepened by considering the following aspects.

4.1 Exploring Boundary Conditions of Action Altering Metacognition

Although numerous studies have shown that action influences metacognition as represented by confidence judgments, other research has found that action does not always affect metacognition, particularly showing no significant effects on key derived metrics such as metacognitive sensitivity, metacognitive efficiency, and confidence-accuracy regression slopes. For example, Charles et al. (2020) compared three conditions: voluntary action (participants moved themselves), passive action (a robotic hand moved participants' fingers), and observational action (participants watched finger movements in a video). The results showed that for perceptual judgments, voluntary action yielded the highest accuracy, while no difference existed between passive and observational actions. For confidence ratings, voluntary action produced the highest scores, passive action was intermediate, and observational action was lowest, yet metacognitive sensitivity and efficiency did not differ significantly across the three conditions. Different action conditions provided different information: voluntary action relied on interoception, proprioception, and visual-temporal cues; passive action depended on proprioception and visual-temporal cues; while observational action relied only on visual-temporal cues. These different information sources may bias confidence ratings but do not alter metacognitive ability. Additionally, Filevich et al. (2020) compared explicit versus implicit perceptual judgments on metacognition and unexpectedly found no differences in metacognitive performance (whether in regression coefficients or metacognitive efficiency). Moreover, when participants were required to make real-time stimulus feature judgments, although confidence ratings increased, metacognitive performance remained unchanged. They concluded that metacognitive evaluation does not always integrate action information.

These findings suggest that action's effects on metacognitive performance and ability are inconsistent, indicating that boundary conditions may exist for action's influence on metacognition. One possible explanation is that confidence rating metrics (Gajdos et al., 2019) differ substantially from derived metacognitive metrics based upon them (Fleming & Lau, 2014; Rausch et al., 2023), with different metrics potentially reflecting different effects and cognitive processing mechanisms. Another possible explanation is that metacognition exhibits high stability and is difficult to alter in certain contexts (Charles et al., 2020; Filevich et al., 2020); particularly when experimental or perceptual tasks are complex, cognitive resources are devoted to task monitoring and execution, leaving insufficient resources for proper metacognitive evaluation. The applicability of these two hypotheses and their explanatory power for experimental results require further empirical verification. Investigating key boundary conditions will help deepen understanding of the stability of associations and organizational structures between perceptual and metacognitive evidence. Specifically, research should examine which aspects of action information—such as response speed (Patel et al., 2012), action intensity (Gajdos et al., 2019), response sequence (Wokke et al., 2020), action conflict (Siedlecka et al., 2020), and action observation (Palmer et al., 2016)—participate in metacognitive processing with what weights, and whether they relate to metacognitive judgments in linear or nonlinear combinations. Furthermore, future work could explore whether action information from different sensory modalities influences metacognition through cross-modal integration (Scheliga et al., 2023).

4.2 Rethinking Metacognition—What Exactly Is Confidence?

To understand how action information influences perceptual confidence, we must first clarify what perceptual confidence means. One perspective holds that perceptual confidence reflects the probability that a decision is correct (e.g., Sanders et al., 2016). Another perspective argues that confidence reflects the amount of evidence favoring a decision while being relatively insensitive to evidence against it (e.g., Samaha & Denison, 2022; Samaha et al., 2019); in other words, people rely excessively on evidence consistent with their decision during confidence judgments, adopting suboptimal heuristic strategies rather than optimal computational strategies that consider inconsistent evidence.

Maniscalco et al. (2021) proposed the differential tuned inhibition theory, which further supports the view that confidence reflects evidence amount. This theory posits that neurons are inhibited by other neurons with opposite tuning preferences, with the degree of inhibition determining the neuron's role in perceptual discrimination and confidence judgments. Specifically, strongly inhibited differencing neurons encode different perceptual interpretations (e.g., left or right) and drive perceptual decisions, whereas weakly inhibited accumulation neurons encode evidence biased toward one perceptual interpretation while ignoring others (e.g., right), driving confidence judgments. Therefore, high-tuned inhibitory neurons compute relative evidence for perceptual interpretations and determine perceptual decisions, while low-tuned inhibitory neurons compute absolute evidence and determine confidence judgments; different tuned inhibitory neurons lead to the separation between perception and confidence. The model proposed by Mamassian and de Gardelle (2022) suggests that confidence in perceptual decisions stems from subjective estimates of self-consistency in perceptual responses—that is, the probability of making the same decision under identical conditions. In signal detection theory terms, whereas traditional confidence definitions emphasize decision accuracy, this confidence definition emphasizes a certain sensitivity in participants that is unaffected by bias. This definition of confidence can well explain illusions, where participants consistently make the same incorrect decision. Traditional confidence theory would consider this an overestimation of confidence (subjective probability of being correct), whereas Mamassian and de Gardelle's (2022) model argues that participants in such cases have good self-consistency rather than overestimated confidence. To some extent, this model also supports the view that confidence reflects the amount of evidence favoring a decision. Recent research has also linked confidence to prior beliefs about tasks (Van Marcke et al., 2024) or suggested that confidence itself is the target rather than the outcome of metacognitive monitoring (Lee et al., 2023).

Both perspectives on "what confidence reflects" can explain the effects of action on confidence. On one hand, if confidence reflects the probability that a decision is correct, then information such as action response speed and intensity can influence subjective assessments of that decision's correctness, so faster response speeds and greater response intensities would both increase confidence. On the other hand, if confidence reflects the amount of evidence favoring a decision, then the addition of action information would alter neuronal tuning, so faster action response speeds and greater response intensities would reduce neuronal tuned inhibition, thereby increasing confidence. However, behavioral measures cannot distinguish between these two hypotheses about the content of confidence. A possible research direction involves combining neuroscientific methods with manipulations of action information such as response speed (Patel et al., 2012) and action intensity (Gajdos et al., 2019), using key neural measures to explore neural correlates of metacognition (NCM) for the two confidence hypotheses that are behaviorally indistinguishable but have clearly different predictions (Overhoff et al., 2021). Based on previous research, two key EEG components—the posterior error positivity (Pe) and centro-parietal positivity (CPP)—may be associated with the two confidence hypotheses respectively, helping to differentiate them. Specifically, Pe occurs 200-400 ms after perceptual judgments, with amplitude increasing as individuals' confidence in error judgments increases, reflecting monitoring of perceptual judgment correctness (Boldt & Yeung, 2015; Feuerriegel et al., 2022). CPP typically occurs after stimulus presentation and before participants make perceptual judgments, with amplitude increasing as confidence grows (Gherman & Philiastides, 2015; Rausch et al., 2020), reflecting the accumulation of evidence supporting the chosen option (Kelly et al., 2021; Philiastides et al., 2014). For example, Ko et al. (2024) identified CPP time windows using two analytical approaches: one 350-500 ms after stimulus presentation, and another 130-70 ms before response. The study also found that neural responses reflecting evidence accumulation could still be observed at electrode sites during the response phase after perceptual judgments and before confidence judgments, a component termed "post-choice CPP" (Grogan et al., 2023). Therefore, confidence hypothesis one (confidence reflects decision correctness) may be associated with Pe, whereas confidence hypothesis two (confidence reflects evidence accumulation) may be associated with CPP. Future research could further differentiate these confidence hypotheses by comparing the correlation between these two NCMs and confidence ratings under manipulations of action information. In short, only by clarifying the true psychological content reflected by confidence can we better explain the cognitive and neural mechanisms of how action alters metacognition.

4.3 Exploring Metacognitive Performance in Special Populations

Currently, most research has focused on healthy adult populations. Studies have found that TMS stimulation of the premotor cortex affects metacognition in healthy individuals (Fleming et al., 2015). Does the action-metacognition relationship also become affected in populations with motor disorders? Research indicates that patients with motor disorders have difficulty inferring confidence in others' actions. Macerollo et al. (2015) used the same observation paradigm as Patel et al. (2012) to compare the performance of Parkinson's patients, patients with functional motor disorders (such as functional tremor or dystonia), and healthy individuals in inferring confidence from others' actions. The results showed that all participants exhibited a negative correlation between speed and confidence inference—the slower the observed speed, the lower the confidence inference. However, further analysis revealed that when individuals in the videos moved the marble at faster speeds during perceptual judgments, healthy participants' confidence inferences were significantly higher than those of patients with motor disorders, indicating that the motor execution system plays a role in inferring confidence from observed actions.

Additionally, some studies have examined metacognitive performance in neurological patients with motor disorders (such as basal ganglia lesions, neurodegenerative diseases, white matter disorders, and acquired brain injuries). These studies primarily compared differences between neurological patients and normal participants in detecting self- or other-action errors. A recent review (Pezzetta et al., 2022) summarized relevant findings, noting that although neurological patients did not show obvious abnormalities in behavioral error processing, most exhibited significantly reduced ERN amplitudes in EEG, particularly when evaluating self-generated error responses.

Furthermore, research on the association between action and metacognition needs to strengthen investigations of two representative special populations. The first is children with autism. Although they typically do not have significant motor disorders, some exhibit non-standard postural control and show clear differences from typically developing children in gait, upper limb movements, and fine motor control (Cook, 2016). Existing research indicates mutual influences between perception and action in autistic children, but the relationship between their motor performance and metacognitive performance requires further investigation. The second special population is paraplegic spinal cord injury patients. These patients have no organic lesions in motor and sensory centers, peripheral effectors, or peripheral nervous systems; however, due to spinal cord injury, neural signal transmission between the brain and effectors/sensors is completely severed. Although some studies have shown that perceptual decision-making differs in spinal cord injury patients compared to healthy individuals (see review Moro et al., 2022), an unexplored question concerns the extent to which pure somatic deafferentation and motor deefferentation affect the association between action and metacognition. In conclusion, studying metacognitive performance in special populations with atypical actions or motor disorders can help reveal the necessary conditions and specific mechanisms through which action influences metacognition.

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Note: Figure translations are in progress. See original paper for figures.