




# Neural correlates of metacognition: Disentangling the brain circuits underlying prospective and retrospective second-order judgments through noninvasive brain stimulation

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## Abstract

Metacognition encompasses the capability to monitor and control one's cognitive processes, with metamemory and metadecision configuring among the most studied higher order functions. Although imaging experiments evaluated the role of disparate brain regions, neural substrates of metacognitive judgments remain undetermined. The aim of this systematic review is to summarize and discuss the available evidence concerning the neural bases of metacognition which has been collected by assessing the effects of noninvasive brain stimulation (NIBS) on human subjects' metacognitive capacities. Based on such literature analysis, our goal is, at first, to verify whether prospective and retrospective second-order judgments are localized within separate brain circuits and, subsequently, to provide compelling clues useful for identifying new targets for future NIBS studies. The search was conducted following the preferred reporting items for systematic reviews and meta-analyses guidelines among PubMed, PsycINFO, PsycARTICLES, PSYINDEX, MEDLINE, and ERIC databases. Overall, 25 studies met the eligibility criteria, yielding a total of 36 experiments employing transcranial magnetic stimulation and 16 ones making use of transcranial electrical stimulation techniques, including transcranial direct current stimulation and transcranial alternating current stimulation. Importantly, we found that both perspective and retrospective judgments about both memory and perceptual decision-making performances depend on the activation of the anterior and lateral portions of the prefrontal cortex, as well as on the activity of more caudal regions such as the premotor cortex and the precuneus. Combining this evidence with results from previous imaging and lesion studies, we advance ventromedial prefrontal cortex as a promising target for future NIBS studies.

## KEYWORDS

awareness, human experimentation, physical stimulation, prefrontal cortex

[Correction added on May 21, 2024 after first online publication. The affiliations of the author 'Antonio Malgaroli' has been updated in this version.]

Mattia Ferro and Jacopo Lamanna are co-last authors of this article

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## 1 | INTRODUCTION

Metacognition is defined as any knowledge or cognitive activity that takes as its object, or regulates, any aspect of any cognitive enterprise (Flavell, 1992). What we know about our thoughts and how we react to them are crucial components of psychological functioning, to such an extent that they constitute a watershed between mental health and human psychopathology. Indeed, current literature highlights that an ineffective metacognitive monitoring characterizes many psychiatric conditions, including major depression, anxiety disorders, obsessive-compulsive disorder, eating disorders, and substance addiction (Sun et al., 2017). Alongside the clinical psychology research strand, neuroscientists have historically made several attempts to quantify executive functions and wire them to the activation of restricted brain areas (Perone et al., 2018), yet little is known with regard to the neural basis of higher order cognition. In cognitive neuroscience, metacognition is split into two main components, which stem from the seminal works of Flavell and Wellman (1977). First, metacognitive knowledge, or meta-knowledge, is conceptualized as the awareness individuals have with respect to their own cognitive processes and their capacity to monitor and reflect on them. Second, metacognitive control, or meta-control, consists in a set of self-regulatory mechanisms, for example, planning and adapting one's own behavior based on the outcomes it produces on the environment (Livingston, 2003). According to the model of Nelson and Narens (1994), meta-knowledge represents the flow and processing of information spanning from the object level to the meta-level, whereas meta-control constitutes the flux running from the meta-level to the object level. The object level envelops multiple cognitive functions, such as recognition and discrimination of items, semantic encoding, spatial representation, and decision-making strategies. Information originating from the object level is then processed on the meta-level, where top-down regulation on lower level cognitive functions is imposed (Nelson, 1990).

Based on this theory, neuroscientists worked out numerous experimental paradigms, for example, Judgment-of-Learning (JOL), Felling-of-Knowing (FOK), and two-Alternative Forced Choice (2-AFC) tasks, in which subjects are asked to make judgments on how confident they are with regard to the decisions they make or the given material they learn (for a review, see Fleur et al., 2021). These judgments are commonly referred to as second-order judgments and they can be considered as a specific form of meta-knowledge (Schwartz, 1994). Considering their temporal focus, metacognitive judgments can be either prospective, that is, predictions of future performances, or retrospective, that is, thoughts referred to the accuracy of past responses. Eliciting a sequence of second-order judgments within an experimental setting represents a unique opportunity to retrieve a solid quantification of metacognition. Since Flavell and Wellman's (1977) early theorizing, a variety of measures has been singled to assess the ability to recognize one's own successful cognitive processing (Fleming & Lau, 2014). The coefficients  $\phi$  ( $\phi$ ) and  $\gamma$  ( $\gamma$ ), for instance, reflect the degree of correlation between accuracy and confidence over trials and, more importantly, are considered as reliable quantitative indexes of metacognitive sensitivity, that is, how well one's confidence ratings

### Significance

Metacognition, that is, the capability to monitor and control one's cognitive processes, represents a key issue for clinical psychologists due to its involvement across many psychiatric disorders. In neuroscience, however, metacognition is less explored, with meta-knowledge and meta-control representing the primary areas of interest. This systematic review examines how noninvasive brain stimulation affects human metacognition, aiming to uncover its neural foundations. Discovering such substrates would pave the way for the development of further therapeutic options, which precisely act on metacognitive abnormalities and, thus, enhance patients' quality of life.

distinguish between correct and incorrect judgments (Nelson, 1984). However, these measures have been demonstrated to be susceptible to the influence of common response biases (Masson & Rotello, 2009). A number of theoretically bias-free methods have thus been developed to assess metacognitive sensitivity, including the type 2  $d'$ , that is, a parametric index based on the assumption that the distribution of internal signals for "correct" and "incorrect" trials are Gaussian with equal variances (Green & Swets, 1966), the Area Under the type 2 ROC curve (AUROC2), that is, a nonparametric method that is free from the equal-variance Gaussian assumption (Clarke et al., 1959), and the meta- $d'$ , that is, a model-based approach which allows the control over the influence of task performance on metacognition (Maniscalco & Lau, 2014).

Dated lesion studies that exploited the experimental apparatus mentioned above highlighted the key role of the frontal lobe in second-order judgments about memory performance (e.g., Janowsky, Shimamura, Kritchevsky, et al., 1989; Pannu et al., 2005). This evidence is consistent with the results of recent neuroimaging works demonstrating the involvement of a frontoparietal network in metacognitive judgments across dissimilar domains, for example, memory monitoring (or metamemory) and perceptual decision-making (or metadecision). Metamemory, that is, any judgment that is made about a memory, especially requires the activation of parietal and midline prefrontal cortex (PFC) regions, whereas metadecision, that is, any judgment that is made about a decision, recruits frontal areas, such as anterior cingulate cortex, insula, and lateral anterior PFC (Baird et al., 2013; Rouault et al., 2018). Advanced imaging studies report that changes in visual metacognitive sensitivity correlate with gray matter volume of frontal polar regions, while changes in memory metacognitive sensitivity correlate with volume of precuneus (Fleming et al., 2010; McCurdy et al., 2013). However, a weak relationship between visual metacognitive sensitivity and precuneus volume has been observed as well, meaning that this structure might contain common mechanisms for both types of metacognitions (McCurdy et al., 2013).

Although most of the neuroscientific research evaluates metacognition across dissimilar domains, only a few experimental studies aimed to identify the neural substrates of second-order judgments by characterizing and manipulating their temporal focus. On this matter, there is considerable evidence that damage to the PFC selectively affects the accuracy of metacognitive reports while leaving task performance relatively intact. Intriguingly, imaging data show that rostral and dorsal portions of the lateral PFC sustain retrospective judgments, while the medial PFC supports prospective judgments (Fleming & Dolan, 2012; Schnyer et al., 2005). Consistent with these findings, causal studies highlight that dorsolateral PFC stimulation and ventromedial PFC damages produce significant alterations in both types of judgments (e.g., Chua et al., 2017; Gaynor & Chua, 2019; Modirrousta & Fellows, 2008; Rounis et al., 2010; Shekhar & Rahnev, 2018). Even though frontal lobes are essential for higher order cognition, many other brain regions are recruited during metamemory and metadecision tasks. Neuroimaging studies (Chua et al., 2009; Irak et al., 2023), in fact, demonstrate that not only medial PFC but also temporoparietal junction, superior temporal gyrus, inferior parietal lobule, and posterior cingulate cortex are implicated in both prospective and retrospective judgments about memory performances. Figure 1 shows a summary of the state of the art concerning this topic.

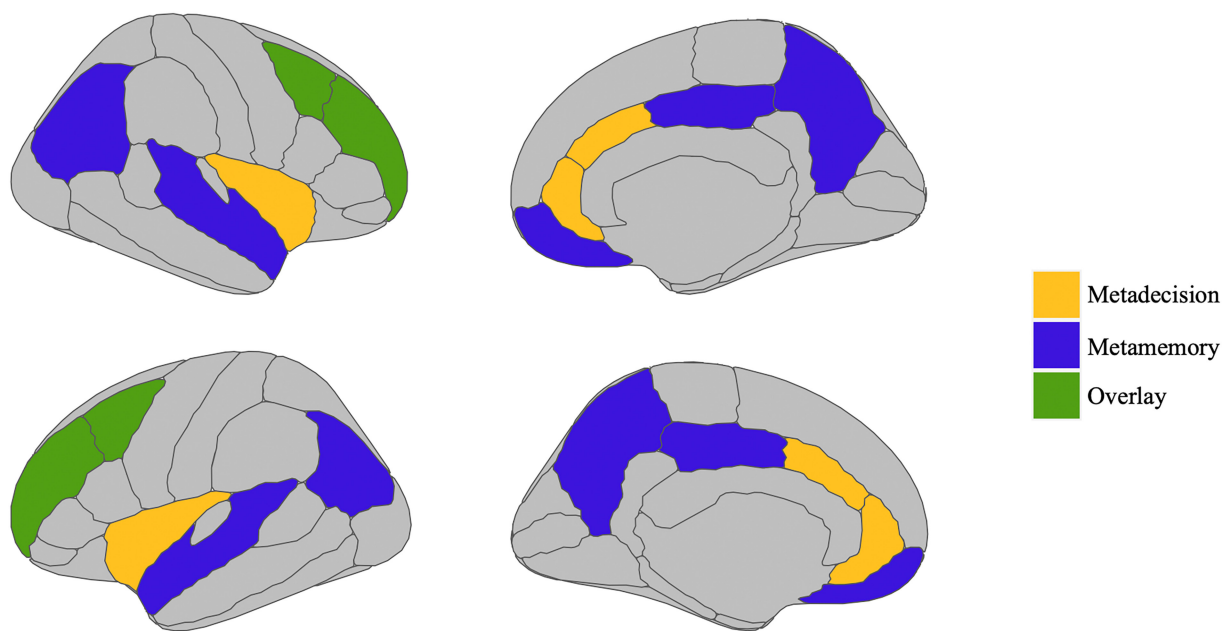
Therefore, the neuronal architecture underlying metacognition remains poorly understood due to inherent methodological and technical limitations. One of the most remarkable lacunes within the current literature concerns, especially the involvement of distinct

neural circuits supporting prospective and retrospective second-order judgments, respectively. A valid approach to fill this gap is to stimulate specific cerebral regions while subjects are engaged in metamemory or metadecision tasks. In this context, noninvasive brain stimulation (NIBS) represents a precious nonpharmacological tool for such investigations, because it makes possible to test the hypothesis that metacognitive judgments, and thus metacognition, are strictly dependent upon the activity of a specific brain area, by transiently modulating its activity, and evaluate metacognitive effects. In fact, NIBS techniques employ electrical and/or magnetic energy to modulate the excitability of the underlying cerebral cortex in a noninvasive fashion and potentially induce long-lasting neuroplastic changes (Ferro et al., 2022).

The broad objective this systematic review addresses is to shed light on the neural substrates of metacognition. More specifically, we aim first to verify whether prospective and retrospective second-order judgments are localized within separate brain areas and, subsequently, to indicate evidence useful for identifying new targets for future NIBS studies.

## 2 | METHOD

The review was implemented using the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines in order to ensure systematicity and replicability of the results (Page et al., 2021).



**FIGURE 1** Overview of the brain regions enlisted in metadecision (in yellow), that is, anterior cingulate cortex and insula, together with brain areas recruited in metamemory tasks (in blue), that is, precuneus, superior temporal gyrus, inferior parietal lobule, posterior cingulate cortex, and ventromedial prefrontal cortex. Dorsolateral and frontopolar cortex ensue implicated in both metamemory and metadecision (in green). Image generation was facilitated through the utilization of the R package *ggseg* (Mowinckel & Vidal-Piñeiro, 2020), which features data from the Desikan-Killiany cortical atlas (Desikan et al., 2006) and the Automatic Segmentation of Subcortical Structures (Fischl et al., 2002).

## 2.1 | Search formula

To identify the included scientific articles, the following electronic databases were searched: PubMed and EBSCOhost, which incorporates records retrieved from PsycINFO, PsycARTICLES, PSYINDEX, MEDLINE, and ERIC. The last search was performed on July 15, 2023 using the same search formula for both databases: ((metacognition) OR (metacognitive judgment) OR (metacognitive awareness) OR (metacognitive knowledge)) AND ((transcranial direct current stimulation) OR (tDCS) OR (transcranial magnetic stimulation) OR (TMS) OR (continuous theta burst stimulation) OR (cTBS) OR (intermittent theta burst stimulation) OR (iTBS) OR (transcranial alternating current stimulation) OR (tACS) OR (transcranial electric stimulation) OR (tES) OR (transcranial random noise stimulation) OR (tRNS)). Additional material was identified through manual selection.

## 2.2 | Study screening and selection process

The first author ran the searches in the electronic databases, identified relevant studies, and removed duplicate titles using Zotero software (Version 6.0.21). The second and the first author independently screened all records at the level of title and abstract based on the inclusion/exclusion criteria determined in advance. Inclusion and exclusion criteria were then applied for full-text screening. In cases of missing data, the authors were contacted to provide original reports. Those cases that remained unclear were further discussed with the remaining authors of the review.

Regarding the eligibility of studies relevant to understanding the neural substrates of metacognition, the PICOS (Participants, Intervention, Comparison, Outcome measure, and Study design) method was adopted (Bowling & Ebrahim, 2005). The review was limited to studies written in the English language, without applying any temporal restriction. To be included in the systematic review, studies should meet the following inclusion criteria:

- **Participants:** Studies conducted on adult participants (i.e., of 18 years of age or older) with or without a psychiatric diagnosis according to the criteria of Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5; American Psychiatric Association, 2013) or the ones of Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, Text Revision (DSM-5-TR; APA, 2022).
- **Intervention:** Studies in which NIBS was delivered as an online or offline intervention, that is, before or during the completion of a metamemory or metadecision task, respectively. Both transcranial magnetic stimulation (TMS) and transcranial electrical stimulation (tES), also including transcranial direct current Stimulation (tDCS), transcranial alternating current stimulation (tACS), and transcranial random noise stimulation (tRNS), were considered as eligible treatments.

- **Comparison:** Studies that involve at least one control group or condition, which could be either sham, that is, inactive, stimulation, or active stimulation on a control site, for example, Vertex.
- **Outcome measure:** Studies that evaluated potential changes in participants metacognitive sensitivity, that is, the ability to discriminate one's own correct and incorrect higher order judgments, or metacognitive efficacy, that is, the level of metacognitive sensitivity when controlling for task performance. With respect to metacognition-related indicators, both parametric and nonparametric correlation measures, for example,  $\phi$  or  $\gamma$  coefficients, and signal detection theory (SDT)-based indexes (Green & Swets, 1966), for example, type 2  $d'$  or meta- $d$ , were considered as reliable indicators of metacognitive sensitivity (Fleming & Lau, 2014).
- **Study design:** All types of quantitative empirical research were included, as long as they met the above-mentioned inclusion criteria.

Studies were excluded from the systematic review when:

- The sample included children, adolescents (i.e., of 16 years of age or below), or animal models.
- The stimulation was delivered invasively, for example, through the implantation of electrodes in the brain, or coupled with the administration of drugs.
- Metacognitive sensitivity was not assessed or compared among groups or conditions.
- They were nonoriginal research studies (e.g., secondary sources, opinion-based, editorials, policy reviews and statements, commentaries), Master level dissertations, conference presentations, conference proceedings where full-length articles are not available, single-case studies, narrative articles or reviews, meta-analyses. Papers whose full text in the English language was not accessible were also excluded.

## 2.3 | Data extraction and quality assessment

The following data were extracted from each included study: article identifiers (i.e., authors and year of publication); sample size; participant diagnosis; targeted brain areas, stimulation protocol applied to the treatment group (TC); stimulation protocol applied to the control group (CG); current or stimulation intensity; task domain; judgments temporal focus; intervention procedure, indexes used for assessing metacognition; effect of stimulation on metacognition.

The mixed methods appraisal tool (MMAT; Hong et al., 2018) was used to critically evaluate the quality and risks of bias in the reviewed studies as well as to ensure that they were reviewed with equal rigor. The MMAT was chosen because it comprises five subsections covering the methodological quality appraisal of randomized controlled trials, nonrandomized studies, and quantitative descriptive studies.

### 3 | RESULTS

As shown in the PRISMA flow chart (Figure 2), 79 records were identified from searching across six databases. Following duplicate removal, a total of 42 records were screened at the title and abstract level. Handpicked searches from articles references generated seven relevant records which were considered for the full-text screening. Then, 35 records (28 from the databases and 7 from handpicked searches) were evaluated for the full-text eligibility. Three studies were excluded as they did not assess participants' metacognitive efficacy nor their metacognitive sensitivity (Chiang et al., 2014; Leitão et al., 2017; Peters et al., 2017); one was excluded because it was a computer simulation of the work published by Bor et al. (2017), Ruby et al. (2018), and two studies were excluded since participants were monkeys instead of humans (Cai et al., 2022; Washburn et al., 2010); one systematic review (Lajoie et al., 2021), one meta-analysis (Mojtabavi et al., 2022), and two Master level dissertations were also kept out from this work. Overall, 25 studies met the inclusion criteria for the data extraction process, and thus, they were included in the systematic review (Bona & Silvanto, 2014; Bor et al., 2017; Carbajal et al., 2019; Chua & Ahmed, 2016; Chua et al., 2017; Di Luzio et al., 2022; Fleming et al., 2015; Gaynor & Chua, 2017, 2019; Gogulski et al., 2017; Han et al., 2023; Hobot et al., 2023; Lapate et al., 2020; Meiron & Lavidor, 2014; Miyamoto et al., 2021; Rahnev et al., 2016; Rounis et al., 2010; Ryals et al., 2016; Schauer et al., 2020; Shekhar & Rahnev, 2018; Xue et al., 2023; Ye et al., 2018, 2019; Zizlsperger et al., 2016; Zou & Kwok, 2022).

### 3.1 | Effects of transcranial magnetic stimulation on metacognition

Table 1 reports a summary of the characteristics of included studies that made use of TMS ( $n=16$ ). Notably, in most of the studies, more than one experiment was performed, varying, for instance, the stimulation site, the protocol delivered, or the task's domain. Hence, each of these experiments were separately reported and described into detail ( $n=36$ ). Seven studies were conducted in the United States of America (Carbajal et al., 2019; Fleming et al., 2015; Lapate et al., 2020; Rahnev et al., 2016; Ryals et al., 2016; Shekhar & Rahnev, 2018; Xue et al., 2023), three were conducted in China (Ye et al., 2018, 2019; Zou & Kwok, 2022), three were conducted in the United Kingdom (Bor et al., 2017; Miyamoto et al., 2021; Rounis et al., 2010), one was conducted in Italy (Di Luzio et al., 2022) one was conducted in Finland (Gogulski et al., 2017), and one was conducted in Denmark (Hobot et al., 2023). All studies were performed on healthy subjects.

#### 3.1.1 | Retrospective second-order judgments

In the majority of the experiments, that is, 31 out of 36, the effects of TMS on retrospective metacognitive judgments were tested, accounting for both domains of memory and perception. Rounis et al. (2010) applied continuous theta-burst stimulation (cTBS) to bilaterally depress the activity of dorsolateral PFC (dlPFC) as subjects performed a visual discrimination task involving retrospective

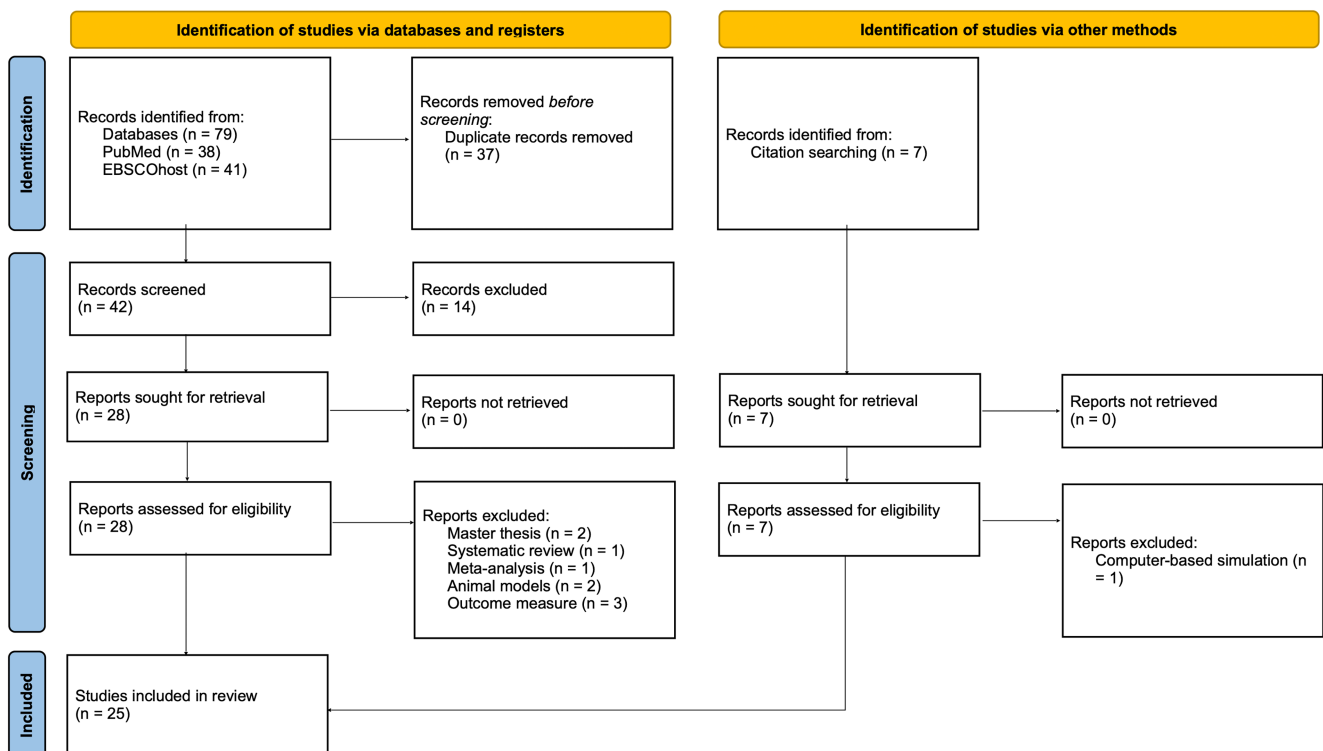


FIGURE 2 PRISMA flowchart diagram. From Page et al. (2021). For more information, visit: <http://www.prisma-statement.org/>.

TABLE 1 Summary of the study making use of transcranial magnetic stimulation.

ID	N	Brain site TG	Protocol TG	Brain site CG	Protocol CG	Stimulation intensity	Procedure	Domain	Temporal focus	Metacognition assessment	Effect
Shekhar and Rahnev (2018)	21	Right dlPFC	Single pulse	Right S1	Single pulse	90% MT	Online	Perception	Retrospective	Mratio	-
Shekhar and Rahnev (2018)	21	Right aPFC	Single pulse	Right S1	Single pulse	90% MT	Online	Perception	Retrospective	Mratio	Increased metacognition
Zou and Kwok (2022)	20	Left AnG	Low frequency rTMS	Vertex	Low frequency rTMS	110% MT	Offline	Memory	Retrospective	Mratio	-
Fleming et al. (2015)	8	Right dPC	Single pulse	Right M1	Single pulse	90% MT	Online	Perception	Retrospective	Mratio	Decreased metacognition
Fleming et al. (2015)	8	Left dPC	Single pulse	Left M1	Single pulse	90% MT	Online	Perception	Retrospective	Mratio	Decreased metacognition
Gogulski et al. (2017)	15	Left SFG	Single pulse	Vertex	Single pulse	110% MT	Online	Memory	Retrospective	Meta-d'-d'	Increased metacognition
Gogulski et al. (2017)	15	Left MFG	Single pulse	Vertex	Single pulse	110% MT	Online	Memory	Retrospective	Meta-d'-d'	-
Gogulski et al. (2017)	15	Left SFG	Single pulse	Vertex	Single pulse	110% MT	Online	Memory	Retrospective	Meta-d'-d'	-
Gogulski et al. (2017)	15	Left MFG	Single pulse	Vertex	Single pulse	110% MT	Online	Memory	Retrospective	Meta-d'-d'	-
Ye et al. (2018)	18	Right precuneus	Low frequency rTMS	Vertex	Low frequency rTMS	110% MT	Online	Memory	Retrospective	Meta-d'-d', log Mratio, $\phi$	Decreased metacognition
Ye et al. (2018)	18	Right precuneus	Low frequency rTMS	Vertex	Low frequency rTMS	110% MT	Online	Perception	Retrospective	Meta-d'-d', log Mratio, $\phi$	-
Ye et al. (2019)	18	Right precuneus	Low frequency rTMS	Vertex	Low frequency rTMS	110% MT	Offline	Memory	Retrospective	Log Mratio, $\phi$	Decreased metacognition
Ye et al. (2019)	18	Right precuneus	Low frequency rTMS	Vertex	Low frequency rTMS	110% MT	Offline	Perception	Retrospective	Log Mratio, $\phi$	-
Rounis et al. (2010)	20	Bilateral dlPFC	cTBS	Bilateral dlPFC	Sham	80% MT	Offline	Perception	Retrospective	Meta-d'-d', $\phi$	Decreased metacognition
Bor et al. (2017)	12	Bilateral dlPFC	cTBS	Vertex	cTBS	80% MT	Offline	Perception	Retrospective	Meta d'-d', Type II d', $\phi$	-
Bor et al. (2017)	10	Bilateral PPC	cTBS	Vertex	cTBS	80% MT	Offline	Perception	Retrospective	Meta d'-d', Type II d', $\phi$	-
Bor et al. (2017)	10	Left dlPFC and PPC	cTBS	Vertex	cTBS	80% MT	Offline	Perception	Retrospective	Meta d'-d', Type II d', $\phi$	-
Bor et al. (2017)	9	Right dlPFC and PPC	cTBS	Vertex	cTBS	80% MT	Offline	Perception	Retrospective	Meta d'-d', Type II d', $\phi$	-
Bor et al. (2017)	17	Bilateral dlPFC	cTBS	Vertex	cTBS	80% MT	Offline	Perception	Retrospective	Meta d'-d', Type II d', $\phi$	-
Rahnev et al. (2016)	17	Right aPFC	cTBS	Right S1	cTBS	80% MT	Offline	Perception	Retrospective	Type II AUROC, meta-d', $\phi$	Increased metacognition
Rahnev et al. (2016)	17	Right dlPFC	cTBS	Right S1	cTBS	80% MT	Offline	Perception	Retrospective	Type II AUROC, meta-d', $\phi$	-

TABLE 1 (Continued)

ID	N	Brain site TG	Protocol TG	Brain site CG	Protocol CG	Stimulation intensity	Procedure	Domain	Temporal focus	Metacognition assessment	Effect
Rahnev et al. (2016)	17	Right FEFs	cTBS	Right S1	cTBS	80% MT	Offline	Perception	Retrospective	Type II AUROC, meta-d', $\phi$	-
Ryals et al. (2016)	21	Bilateral aPFC	cTBS	Vertex	cTBS	80% MT	Offline	Memory	Prospective	$\gamma$ , Type II AUROC	Increased metacognition
Ryals et al. (2016)	21	Bilateral dlPFC	cTBS	Vertex	cTBS	80% MT	Offline	Memory	Prospective	$\gamma$ , Type II AUROC	-
Ryals et al. (2016)	21	Bilateral aPFC	cTBS	Vertex	cTBS	80% MT	Offline	Memory	Retrospective	$\gamma$ , Type II AUROC	Increased metacognition
Ryals et al. (2016)	21	Bilateral dlPFC	cTBS	Vertex	cTBS	80% MT	Offline	Memory	Retrospective	$\gamma$ , Type II AUROC	-
Hobot et al. (2023)	21	Left amPFC	cTBS	Left amPFC	Sham	75% MT	Offline	Perception	Retrospective	Mratio	Increased metacognition
Hobot et al. (2023)	21	Left amPFC	iTBS	Left amPFC	Sham	75% MT	Offline	Perception	Retrospective	Mratio	-
Carbajal et al. (2019)	12	Left PFC	cTBS	Vertex	cTBS	80% MT	Offline	Memory	Prospective	$\gamma$	Decreased metacognition
Carbajal et al. (2019)	12	Right PFC	cTBS	Vertex	cTBS	80% MT	Offline	Memory	Prospective	$\gamma$	-
Lapate et al. (2020)	28	Left IPFC	cTBS	Left S1	cTBS	80% MT	Offline	Perception	Retrospective	Type II AUROC, meta d', meta-d'-d'	Decreased metacognition
Lapate et al. (2020)	32	Left IPFC	cTBS	Left S1	cTBS	80% MT	Offline	Perception	Retrospective	Type II AUROC, meta d', meta-d'-d'	-
Miyamoto et al. (2021)	8	Left aIPFC	cTBS	aIPFC	Sham	80% MT	Offline	Perception	Prospective	Type II AUROC	Decreased metacognition
Di Luzio et al. (2022)	17	V5/MT to V1/V2	ccPAS (ISI=20ms)	IPS/LIP to V1/V2	ccPAS (ISI=0ms)	60% TMS output	Offline	Perception	Retrospective	Meta-d'-d'	-
Di Luzio et al. (2022)	17	IPS/LIP to V1/V2	ccPAS (ISI=30ms)	IPS/LIP to V1/V2	ccPAS (ISI=0ms)	60% TMS output	Offline	Perception	Retrospective	Meta-d'-d'	Increased metacognition
Xue et al. (2023)	76	Right dlPFC	Single pulse	Vertex	Single pulse	120% MT	Online	Perception	Retrospective	Meta-d'	-

Abbreviations: aIPFC, anterior lateral prefrontal cortex; amPFC, anterior medial prefrontal cortex; AnG, angular gyrus; aPFC, anterior prefrontal cortex; ccPAS, corticocortical paired associative stimulation; cTBS, continuous theta burst stimulation; dlPFC, dorsolateral prefrontal cortex; dPC, dorsal premotor cortex; FEFs, frontal eye fields; IPS, intraparietal sulcus; ISI, interstimulus interval; LIP, lateral intraparietal cortex; IPFC, lateral prefrontal cortex; M1, primary motor cortex; MFG, middle frontal gyrus; MT, motor threshold; PFC, prefrontal cortex; PPC, posterior parietal cortex; rTMS, repetitive transcranial magnetic stimulation; S1, primary somatosensory cortex; SFG, superior frontal gyrus; TMS, transcranial magnetic stimulation; V5/MT, V5/middle temporal area.

second-order judgments; they found out that TMS induces a decrease in participants' metacognitive sensitivity, while objective performance was kept constant. Bor et al. (2017) attempted to replicate this finding, with minor modifications, but no evidence for metacognitive impairment was found in both between-subject and within-subject experiments. Consistent with these results, Shekhar and Rahnev (2018) employed an online TMS protocol asking participants to perform a perceptual decision-making task and then provided confidence ratings about their choices, finding that TMS on dlPFC produced no effects on metacognition. Nonetheless, participants' metacognitive abilities were increased when the anterior PFC (aPFC) was stimulated (Shekhar & Rahnev, 2018). Rahnev et al. (2016) also identified a clear specialization along the rostro-caudal axis, such that the control of successive stages of perceptual decision-making was selectively affected by the perturbation of successively rostral areas. Indeed, cTBS over aPFC led to increased metacognitive efficiency, whereas the application of the same stimulation protocol over dlPFC or putative frontal eye fields (FEFs) yielded no effects on metacognition (Rahnev et al., 2016). Likewise, Xue et al. (2023) demonstrated that single pulse TMS over dlPFC produced increased confidence in the absence of changes to accuracy or metacognitive efficiency in a visual perceptual decision-making task. Alterations in retrospective second-order judgments were observed through the administration of a visual identification task accompanied by visual awareness ratings after the application of different protocols of TBS over the anterior medial PFC (amPFC). Indeed, an increase in subjects' metacognitive efficiency was detected following cTBS, but not when intermittent theta-burst stimulation (iTBS) was delivered; meanwhile, no significant differences in the identification task performance were found (Hobot et al., 2023). Lapate et al. (2020) applied cTBS over lateral PFC prior to a two face discrimination task followed by subjective reports on the clarity of the visual experience. Data analysis showed a decrease in participants' metacognitive awareness of faces' spatial orientation, but not of faces' expressed emotions, without a significant impact of the stimulation on the overall discrimination accuracy (Lapate et al., 2020). Neural substrates of metadecision were also investigated by Fleming et al. (2015), who delivered TMS over dorsal premotor cortex (dPC) in order to selectively disrupt post-response confidence in visual discrimination judgments, resulting in a reduction of subjects' metacognitive efficiency without any significant alteration in visual discrimination performances.

Intriguingly, by use of corticocortical paired associative transcranial magnetic stimulation (ccPAS), Di Luzio et al. (2022) shaped perceptual sensitivity and metacognitive ability in a motion discrimination task targeting distinct brain networks, demonstrating their functional dissociation. Neurostimulation aimed at boosting V5/middle temporal area (MT)-to-V1/V2 back projections enhanced motion sensitivity without impacting metacognition, whereas boosting intraparietal sulcus (IPS)/lateral intraparietal cortex (LIP)-to-V1/V2 back projections increased metacognitive efficiency without impacting motion sensitivity (Di Luzio et al., 2022).

Turning to metamemory, Gogulski et al. (2017) dissected the neural architecture of somatosensory metacognition using navigated single-pulse TMS to modulate the activity of distinct portions of PFC, namely the superior frontal gyrus (SFG) and the middle frontal gyrus (MFG), while subjects were undergoing a tactile working memory (WM) task comprising confidence ratings of their performances. Authors unveiled that TMS over the SFG selectively enhanced metacognitive accuracy of temporal, but not spatial, tactile WM; whereas neuromodulation of the MFG had no such effect on metacognitive accuracy of either the temporal or spatial tactile WM (Gogulski et al., 2017). Ryals et al. (2016) used TBS to temporarily modulate dorsolateral versus frontopolar prefrontal cortex prior to the completion of an associative recognition task involving retrospective judgments regarding memory awareness and showed that objective memory performance did not differ based on stimulation location, although frontopolar stimulation significantly influenced memory awareness. Alterations in retrospective second-order judgments about memory performances were not found after the application of a repetitive TMS protocol over more caudal brain areas. Indeed, the stimulation of the angular gyrus (AnG) before the retrieval of relevant scenarios of movies previously watched kept metacognitive efficiency as well as objective memory accuracy unaffected (Zou & Kwok, 2022).

Metamemory and metadecision were tested within the same study as well: Ye et al. (2018) focally disrupted medial parietal cortex activity using low-frequency repetitive TMS, aiming at ascertaining its necessity for metacognition about memory versus perceptual decision-making. Perturbing the neuronal activity of precuneus resulted in a selective impairment of metacognitive efficiency regarding temporal order memory judgment, but did not affect perceptual discrimination; moreover, correlation between the two domains of metacognitive efficiency disappeared when the precuneus was perturbed (Ye et al., 2018). Consistent with these findings, the same research group observed a reduction in subjects' metacognitive efficiency following the application of an inhibitory low-frequency repetitive TMS protocol over the precuneus before the completion of a temporal order memory retrieval task, but still no significant alterations in participants' metadecision capacities were detected through a visual discrimination task with the addition of post-response confidence ratings (Ye et al., 2019).

### 3.1.2 | Prospective second-order judgments

The remaining experiments, that is, five out of 36, evaluated the effects of TMS on prospective metacognitive judgments, in which both memory and perception domains were taken into consideration. More specifically, Ryals et al. (2016) applied TBS over dorsolateral and frontopolar aspects of the PFC before short study phases, in which subjects were prompted to make a JOL rating based on the likelihood of remembering pairs of items on a later performed associative recognition test. In these experiments, JOL was more accurate such that lower ratings were given to items that were subsequently forgotten



following frontopolar TBS: a linear increase in memory awareness was observed in relation to TBS locations along the rostrocaudal direction, supporting a spatial hierarchy of prefrontal contributions to metacognition (Ryals et al., 2016). Starting from this evidence, Carbajal et al. (2019) intended to determine if TBS to PFC modulates visual memory accuracy, visual memory awareness, or both, and whether these effects depend on which brain hemisphere is targeted. Making use of a visual associative memory task incorporating global-level awareness judgments and FOK judgments on test trials for which retrieval failed, authors showed that memory accuracy significantly improved after right hemisphere TBS, while subjects proved to be relatively unconfident after right hemisphere TBS; however, the correspondence between FOKs and later recognition accuracy showed a pattern of disruption in prospective memory monitoring accuracy solely after left TBS (Carbajal et al., 2019).

Concerning metadecision, Miyamoto et al. (2021) evaluated the causal role of the anterior lateral PFC (alPFC) in prospective second-order judgments by making use of tTBS and unveiled that alPFC stimulation impaired metacognitive performance compared with no stimulation in a two-stage perceptual decision-making task.

### 3.2 | Effects of transcranial electrical stimulation on metacognition

Tables 2 and 3 report a summary of the characteristics of the included studies that made use of tDCS ( $n=6$ ) and tACS ( $n=3$ ), respectively. No study employed tRNS. As for TMS studies, in most of the tES studies, more than one experiment was performed, varying, for instance, the stimulation site, the protocol delivered, or the task's domain. Hence, each of these experiments was separately reported and described into detail ( $n=16$ ). Five studies were conducted in the United States of America (Chua & Ahmed, 2016; Chua et al., 2017; Gaynor & Chua, 2017, 2019; Han et al., 2023), two were conducted in Germany (Schauer et al., 2020; Zizlsperger et al., 2016), one was conducted in Israel (Meiron & Lavidor, 2014), and one was conducted in Finland (Bona & Silvanto, 2014). All studies were conducted on healthy individuals.

#### 3.2.1 | Retrospective second-order judgments

Almost half the experiments, that is, seven out of 16, evaluated the effects of tES on retrospective second-order judgments, accounting for both domains of memory and perception. Han et al. (2023) made use of high-definition tDCS (HD-tDCS) to seek evidence for the causal role of vIPFC in supporting the memory advantage for high-value items, finding that anodal stimulation of left vIPFC significantly boosted memory encoding selectivity, that is, participants' metacognitive sensitivity, assessed through a recognition test accompanied by post-response confidence judgments. No such effect was observed in subjects who received right vIPFC, while estimates of recollection- and familiarity-based responding showed that left

vIPFC stimulation specifically amplified the effects of item value on recollection (Han et al., 2023). The modulation of dorsal areas of PFC affects retrospective judgments of memory performances as well. Indeed, the application of tACS over bilateral dlPFC during a verbal working memory task increased not only the objective cognitive performance but also the post-stimulation self-evaluations participants made about their performance (Meiron & Lavidor, 2014). In contrast, Bona and Silvanto (2014) administered a delayed cue-target orientation discrimination task with the addition of retrospective second-order judgments and they revealed no effects of dlPFC anodal stimulation on visual short-term memory metacognition; namely, tDCS induced a general reduction in confidence ratings but did not affect subjects' metacognitive sensitivity.

Turning to metadecision, Schauer et al. (2020) made use of tACS to manipulate conscious perception in trials involving binocular rivalry and continuous flash suppression (CFS). The application of tACS across the parieto-occipital cortex (POC) at either the same or different frequency and phase did not differentially affect conscious subjects' perception in the forms of predominance, CFS detection accuracy, reaction time, or metacognitive sensitivity (Schauer et al., 2020). In accordance with these findings, Zizlsperger et al. (2016) showed that the application of tACS over the occipital cortex (OC) during a four-alternative forced choice task with added post-decision wagering produced no significant effects on subjects' metacognitive sensitivity.

#### 3.2.2 | Prospective second-order judgments

The remaining nine out of 16 experiments explored the effects of tES on prospective second-order judgments, with the memory domain being the only one to be considered. Chua and Ahmed (2016) used HD-tDCS to appraise whether the dlPFC plays a causal role in memory monitoring by administering a metamemory task, in which participants were first tempted to remember the answer to a general knowledge question, then gave an FOK judgment, followed by a forced-choice recognition test. Under anodal stimulation of the dlPFC, subjects' FOK judgments were better predictors of memory performance, that is, they showed a higher memory monitoring accuracy compared to stimulation of a control site, that is, the anterior temporal lobe (aTL); furthermore, this effect was specific to metacognition, as no significant increase in objective memory performance was detected (Chua & Ahmed, 2016). In a subsequent study, Gaynor and Chua (2017) applied tDCS over dlPFC during a verbal associative encoding test followed by a JOL task and found opposite results: the intervention impaired associative encoding, but no effects of neuromodulation on metacognitive accuracy were observed. Such finding was, however, disconfirmed by Chua et al. (2017), who delivered HD-tDCS over the dlPFC or the aTL during a general knowledge recall and recognition tests followed by a FOK metamemory task, demonstrating that dlPFC modulation led to improved recognition accuracy as well as improved metacognitive sensitivity with respect to aTL stimulation. Gaynor and Chua (2019)

TABLE 2 Summary of the study making use of transcranial direct current stimulation.

ID	N	Anodal site TG	Cathodal site TG	Protocol TG	Anodal site CG	Protocol CG	Current intensity	Procedure	Domain	Temporal focus	Metacognition assessment	Effect
Chua et al. (2017)	36	Left dlPFC	-	Anodal HD-tDCS	Left dlPFC	Sham	2.0 mA	Online	Memory	Prospective	da	Increased metacognition
Chua et al. (2017)	36	Left aTL	-	Anodal HD-tDCS	Left dlPFC	Sham	2.0 mA	Online	Memory	Prospective	da	-
Gaynor and Chua (2017)	24	Left dlPFC	Right supraorbital ridge	Anodal tDCS	Left SG	Sham	2.0 mA	Online	Memory	Prospective	$\gamma$ , da	-
Gaynor and Chua (2017)	24	Left SG	Right SG	Anodal tDCS	Left SG	Sham	2.0 mA	Online	Memory	Prospective	$\gamma$ , da	-
Bona and Silvano (2014)	15	Right dlPFC	Left supraorbital ridge	Anodal tDCS	Right dlPFC	Sham	2.0 mA	Offline	Memory	Retrospective	$\phi$	-
Han et al. (2023)	21	Left vlPFC	-	Anodal HD-tDCS	Left vlPFC	Sham	2.0 mA	Offline	Memory	Retrospective	da	Increased metacognition
Han et al. (2023)	20	Right vlPFC	-	Anodal HD-tDCS	Right vlPFC	Sham	2.0 mA	Offline	Memory	Retrospective	da	-
Chua and Ahmed (2016)	27	Left dlPFC	-	Anodal HD-tDCS	Left aTL	Anodal HD-tDCS	2.0 mA	Online	Memory	Prospective	da	Increased metacognition
Gaynor and Chua (2019)	24	Left dlPFC	-	Anodal HD-tDCS	Left SG	Sham	2.0 mA	Online	Memory	Prospective	Type II AUROC, $\gamma$ , da	-
Gaynor and Chua (2019)	24	aPFC	-	Anodal HD-tDCS	Left SG	Sham	2.0 mA	Online	Memory	Prospective	Type II AUROC, $\gamma$ , da	Increased metacognition
Gaynor and Chua (2019)	24	Left dlPFC	-	Anodal HD-tDCS	Left SG	Sham	2.0 mA	Online	Memory	Prospective	Type II AUROC, $\gamma$ , da	Decreased metacognition
Gaynor and Chua (2019)	24	aPFC	-	Anodal HD-tDCS	Left SG	Sham	2.0 mA	Online	Memory	Prospective	Type II AUROC, $\gamma$ , da	Decreased metacognition

Abbreviations: aPFC, anterior prefrontal cortex; aTL, anterior temporal lobe; dlPFC, dorsolateral prefrontal cortex; HD-tDCS, high-definition transcranial direct current stimulation; SG, supramarginal gyrus; tDCS, transcranial direct current stimulation; vlPFC, ventrolateral prefrontal cortex.

TABLE 3 Summary of the study making use of transcranial alternating current stimulation.

ID	N	Brain site TG	Protocol TG	Brain site CG	Protocol CG	Current intensity	Procedure	Domain	Temporal focus	Metacognition assessment	Effect
Meiron and Lavidor (2014)	24	Bilateral dlPFC	4.5 Hz tACS	Bilateral dlPFC	Sham	1.0 mA	Offline	Memory	Retrospective	Success-confidence score	Increased metacognition
Zizlsperger et al. (2016)	30	OC	3.0 Hz tACS	Central OC	Sham	1.5 mA	Online	Perception	Retrospective	Type II AUROC	-
Schauer et al. (2020)	19	Bilateral POC	7.2 Hz tACS	Bilateral POC	Sham	1.0 mA	Online	Perception	Retrospective	Type II AUROC	-
Schauer et al. (2020)	19	Bilateral POC	9.0 Hz tACS	Bilateral POC	Sham	1.0 mA	Online	Perception	Retrospective	Type II AUROC	-

Abbreviations: dlPFC, dorsolateral prefrontal cortex; OC, occipital cortex; POC, parieto-occipital cortex; tACS, transcranial alternating current stimulation.

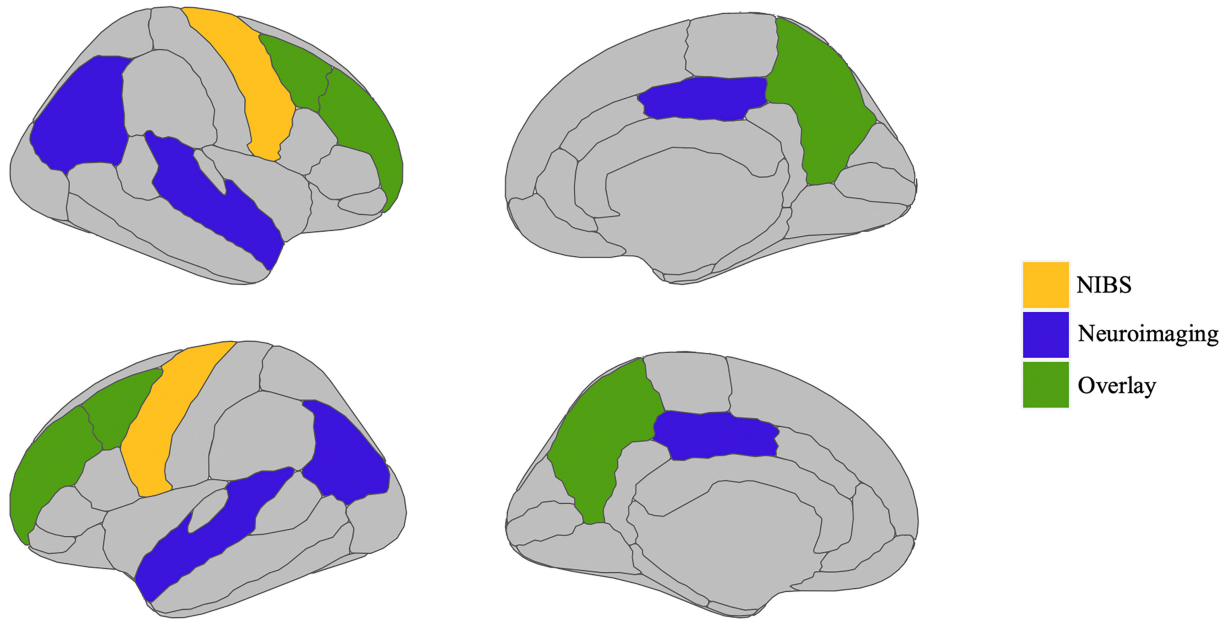
asked participants to study a pool of words that varied in fluency while undergoing HD-tDCS and, then, to make JOLs about them. Besides impairing the encoding process, as evidenced by an increase in subsequent false alarms, dlPFC stimulation decreased metacognitive accuracy for high-frequency words; conversely, aPFC stimulation improved memory monitoring accuracy for low-fluency words and decreased memory monitoring accuracy for high-frequency words, suggesting the roles of these brain regions in metacognition vary along with the cognitive bases of the prospective second-order judgments (Gaynor & Chua, 2019).

## 4 | DISCUSSION

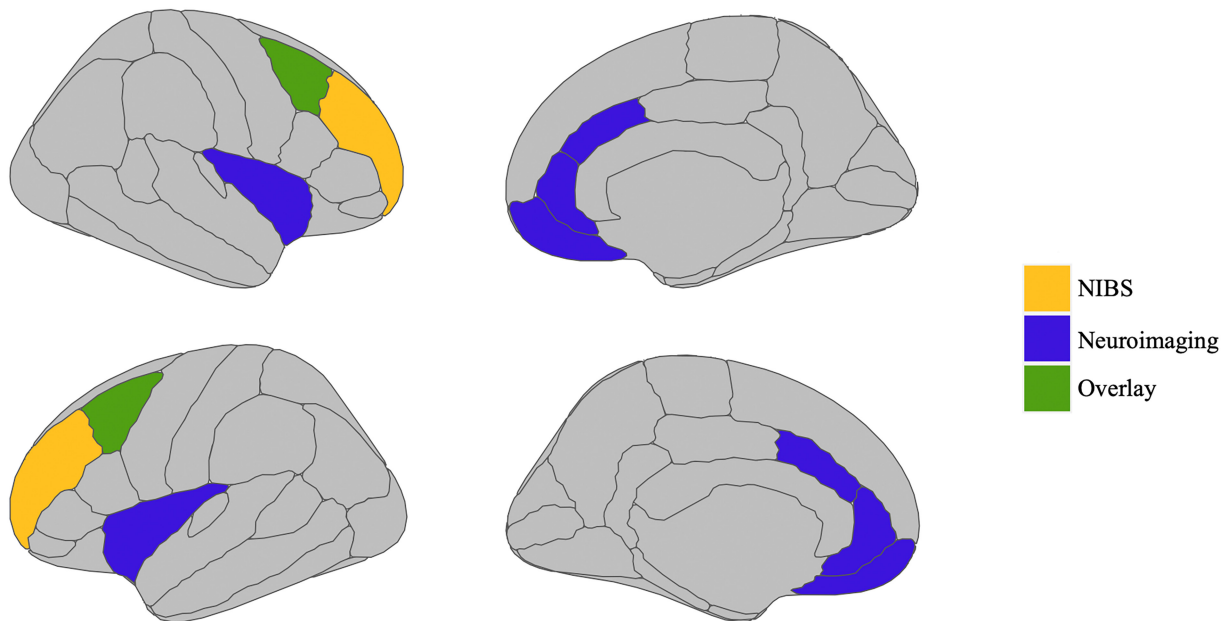
The primary aim of this systematic review was to shed light on the current knowledge about the neural correlates of metacognition, focalizing on whether prospective and retrospective second-order judgments were underpinned by different neuronal circuits, respectively. To achieve this goal, we considered the latest experimental studies that made use of NIBS to transiently perturb participants' metacognitive performances in either metamemory or metadecision tasks. According to the examined literature, metacognition depends on the activation of a heterogeneous set of brain regions, depending not only on the tasks' domain but also on the judgments' temporal focus. For a summary of the present findings, see Figures 3 and 4.

Both aPFC and dlPFC appear as the most involved brain areas in the processing of retrospective second-order judgments about perceptual decision-making performances (Hobot et al., 2023; Rahnev et al., 2016; Rounis et al., 2010; Shekhar & Rahnev, 2018). This is consistent with a voxel-based morphometry analysis, which revealed that variations in visual metacognitive efficiency were correlated with volume of the frontopolar regions during a 2-AFC task added with retrospective confidence ratings (McCurdy et al., 2013). Neuroimaging studies also posit that metacognitive capacities for perceptual decisions are associated with a greater connectivity between the lateral regions of the aPFC and right dorsal anterior cingulate cortex, bilateral putamen, right caudate, and thalamus (Baird et al., 2013).

Among TMS studies on metadecision, the results obtained by Rahnev et al. (2016) are quite of interest, because they are in contrast with previous works suggesting that a transient disruption of the most rostral area of frontal cortex, that is, the aPFC, would have impaired subjects' metacognitive capacities (Fleming et al., 2010, 2012). The observed effect was actually in the opposite direction, namely that cTBS over the rostral aspect of frontal cortex improved metacognition, while leaving the overall task performance unaffected (Rahnev et al., 2016). Previous fMRI studies on such matter highlighted a positive correlation between subjects' metacognitive sensitivity and the level of activation of the rostrolateral PFC (rlPFC) (Yokoyama et al., 2010). Significant relations have also been found between introspective abilities and gray matter volume of rlPFC (Fleming et al., 2010). The involvement of the rlPFC in metacognition may align with its



**FIGURE 3** Overview of the brain regions enlisted in retrospective second-order judgments according to noninvasive brain stimulation (in yellow), that is, dorsal premotor cortex, and neuroimaging (in blue), that is, superior temporal gyrus, inferior parietal lobule, and posterior cingulate cortex. Anterior and dorsolateral prefrontal cortex as well as the precuneus ensue implicated in retrospective second-order judgments according to both NIBS and Neuroimaging studies (in green). Image generation was facilitated through the utilization of the R package *ggseg* (Mowinckel & Vidal-Piñero, 2020), which features data from the Desikan–Killiany cortical atlas (Desikan et al., 2006) and the Automatic Segmentation of Subcortical Structures (Fischl et al., 2002).



**FIGURE 4** Overview of the brain regions enlisted in prospective second-order judgments according to noninvasive brain stimulation (in yellow), that is, anterior prefrontal cortex, and neuroimaging (in blue), that is, anterior cingulate gyrus, insula, and ventromedial prefrontal cortex. Dorsolateral prefrontal cortex results implicated in prospective second-order judgments according to both NIBS and neuroimaging studies (in green). Image generation was facilitated through the utilization of the R package *ggseg* (Mowinckel & Vidal-Piñero, 2020), which features data from the Desikan–Killiany cortical atlas (Desikan et al., 2006) and the Automatic Segmentation of Subcortical Structures (Fischl et al., 2002).

anatomical location at the apex of a cognitive hierarchy, where it receives inputs from other prefrontal regions, the cingulate, and the anterior temporal cortex (Ramnani & Owen, 2004). The rIPFC

likely contributes to metacognitive functions by representing task uncertainty in a manner suitable for interpersonal communication. This proposition finds support in the observation that rIPFC

activation is linked to the evaluation of self-generated information and attention toward internal mental representations (Gilbert et al., 2006; Simons et al., 2008). Evidence from structural brain imaging studies further strengthens this argument, revealing a common neural basis in the aPFC for both reality monitoring and metacognitive sensitivity (Buda et al., 2011). Not only rIPFC but also dlPFC potentially sustains the representation of prior decisions, aligning with its established involvement in WM processes (Curtis & D'Esposito, 2003).

Interesting considerations can be done with regard to metamemory, such that aPFC and dlPFC embody not only the most likely recruited brain regions in the processing of retrospective second-order judgments about memory performances (Gogulski et al., 2017; Han et al., 2023; Meiron & Lavidor, 2014; Ryals et al., 2016) but also constitutes highly probable brain circuits underlying prospective judgments about one's own memory capacities (Carbajal et al., 2019; Chua & Ahmed, 2016; Chua et al., 2017; Gaynor & Chua, 2019; Ryals et al., 2016). This evidence opens the possibility for shared neural substrates between retrospective and prospective second-order judgments regarding memory performances. However, this hypothesis is inconsistent with previous fMRI data, which showed that rostral and dorsal aspects of the lateral PFC sustain retrospective judgments, while the medial PFC supports prospective judgments (Fleming & Dolan, 2012). Furthermore, lesion studies conducted on humans posit that deficits in metacognitive abilities for memory retrieval were predominately associated with lateral frontal damages (Pannu et al., 2005), whereas ventromedial PFC (vmPFC) injuries were linked to a decreased metacognitive sensitivity assessed through an FOK task (Schnyer et al., 2004). In this framework, the role of vmPFC in prospective second-order judgments may be explained by its strong connections with medial temporal lobe memory structures and its involvement in future imagination (Hassabis & Maguire, 2007; Sharot et al., 2007). In contrast, the role of aPFC and dlPFC in retrospective second-order judgments elicited in either metamemory or metadecision tasks may be closely aligned to that of a performance monitor, which integrates and maintains information pertaining to the newly issued responses in order to facilitate an accurate metacognitive functioning (Koechlin et al., 1999; Shimamura, 2000).

Among TMS studies on metamemory, controversial results have been obtained by Ryals et al. (2016), since they demonstrated that the application of cTBS over frontopolar cortex improved, rather than impaired, memory awareness for both retrospective and prospective judgment responses. This observation bears significance if we consider the hypothesis that frontopolar cortex acts as a "capstone" within a rostrocaudal hierarchy for memory awareness, monitoring, and cognitive control (Badre, 2008). Assuming that rostral brain areas receive convergent input from a number of posterior brain regions associated with cognitive functioning (Passingham & Wise, 2012), the enhancements in metacognitive capacities assessed subsequent to the delivery of cTBS over frontopolar cortex could be attributed to an augmented interactivity between the frontopolar cortex and other brain regions implicated in memory

processing. Indeed, Gratton et al. (2013) highlighted an increased functional connectivity within the distributed networks of the PFC following cTBS.

Even though frontal lobes are essential for the processing of higher order cognition, many other brain regions are recruited during metamemory and metadecision tasks. Neuroimaging studies, in fact, demonstrate that not only mPFC and dlPFC but also tempo-parietal junction, superior temporal gyrus, inferior parietal lobule, and posterior cingulate cortex ensue implicated in metacognition (Chua et al., 2009; Irak et al., 2023). Indeed, NIBS studies demonstrated that precuneus and dPC are involved in the processing of retrospective second-order judgments about and memory and perceptual decision-making performance, respectively (Fleming et al., 2015; Ye et al., 2018, 2019). This evidence is consistent with the results of previous lesion studies, claiming that subjects with posterior parietal cortex damages exhibited reduced confidence in their source recollection (Ciaramelli et al., 2017; Simons et al., 2010). Furthermore, fMRI investigations highlighted that a variation in metacognitive efficiency correlates with the volume of precuneus during a metamemory task (McCurdy et al., 2013). Given the involvement of the precuneus in retrospective metacognitive judgments, a natural question to ask is how this brain region is involved in metacognition. In order to address this inquiry, one may examine the study of Ye et al. (2019), who showed that individuals with higher resting-state functional connectivity between the precuneus and the hippocampus were more vulnerable to the inhibitory TMS effects. The ventral region of the precuneus, specifically, has been identified as playing a crucial role in memory-related processes and exhibiting strong connectivity with the hippocampus (Ren et al., 2018; Vincent et al., 2006). Since the hippocampus is essential for temporal-order memory judgments and influences the neural activity associated with confidence judgments as well (Chua et al., 2006; Davachi & DuBrow, 2015), the precuneus may serve as a metamemory accumulator during memory retrieval, relying on its functional connectivity with the hippocampus (Wagner et al., 2005). Animal studies have confirmed such hypothesis, by delineating a distinct metamemory pathway involving information flow from the hippocampus, through the intraparietal cortex, and ultimately read-out by prefrontal brain regions (Miyamoto et al., 2017, 2018). Furthermore, researchers have observed significant correlations between markers of myelination and iron content in the hippocampus and individual differences in metacognition (Allen et al., 2017). These findings suggest that the neuromodulatory effects induced by TMS probably depend on the individuals' functional connectivity between the precuneus and the hippocampus.

Looking at our findings, TMS represents the most effective tool for influencing metacognition, followed by tDCS and tACS. This consideration is, however, vitiated by the number of experiments conducted using NIBS, which shows a large disproportion in favor of TMS. tES has been less implemented in the study of metacognitive knowledge, but preliminary evidence we discussed above suggests that such technique might constitute a valid alternative to TMS for future studies on a tight budget.

Overall, mapping with accuracy the neural substates of higher order thinking appears an arduous task, due to inherent and methodological limitations. First, not only a few, but many brain regions result involved in metacognition, spanning from the frontopolar cortex to the precuneus. According to NIBS studies, aPFC and dlPFC seem to represent the most likely neuronal correlates of both prospective and retrospective second-order judgments, which is a hardly interpretable finding. Second, the stimulation of these specific brain areas also leads to markedly contradictory outcomes even across comparable experimental settings. For instance, Rounis et al. (2010) demonstrate that the application of TMS over bilateral dlPFC induces a decrease in subjects' metacognitive sensitivity, whereas Bor et al. (2017) do not confirm such evidence albeit the usage of an identical task and stimulation protocol. On this matter, authors of the original work made a rebuttal, in which they reported that excluding ~30% of the subjects by Bor et al.'s criteria did not reduce false-positive rates according to a computer-based simulation (Ruby et al., 2018). Moreover, by grouping positive and negative results in a Bayesian framework, PFC stimulation still impaired visual metacognition (Ruby et al., 2018). In response, Bor et al. (2018) argued that such criticisms were misplaced, highlighting the complexity behind the replication of cognitive neuroscientific studies and the necessity to establish clear data exclusion criteria that must be followed when employing STD-based statistical analyses. Third, looking at the NIBS studies from a global perspective, it is impossible not to notice a high heterogeneity in the experimental samples sizes, cognitive tasks, and quantitative indexes used to assess metacognition, which could explain the contradictory results extracted from the included investigations.

Besides these inconsistencies, the most robust and replicable finding entails the recruitment of anterior and lateral portions of PFC in the processing of meta-knowledge, which was observed in both TMS and tES investigations on metamemory and metadecision. More specifically, anodal tDCS over aPFC and dlPFC consistently increase metacognitive sensitivity, whereas low-frequency rTMS and cTBS protocols applied over the same brain sites sort the opposite effect in the majority of cases. Intriguingly, we found no study exploring the effects of vmPFC stimulation on metacognition. To address the secondary aim of this systematic review, we propose the vmPFC as a suitable new target for future NIBS studies. Indeed, the vmPFC is one of the main hubs of the default mode network, which plays a central role in value coding, decision-making, emotional processing, memory, self-perception, and social cognition (Lamanna et al., 2021, 2022; Lopez-Persem et al., 2019). Although NIBS investigations targeting vmPFC are still lacking, there is a long tradition in imaging and lesion studies underlining the involvement of such brain region in metacognition, especially in the processing of prospective second-order judgments (Janowsky, Shimamura, & Squire, 1989; Kao et al., 2005; Modirrousta & Fellows, 2008; Pannu & Kaszniak, 2005; Schnyer et al., 2005; Shimamura & Squire, 1986).

Scientific literature has demonstrated that depressed subjects show impaired metacognitive judgments about their performance in a subsequent executive function task (Drueke et al., 2022). However, no

NIBS studies aimed at assessing the consequences of neuromodulation and plasticity induction on higher order cognitions among psychiatric patients have been found in this review, which pave the way for future experiments (Lamanna et al., 2019; Spadini et al., 2021). Demonstrating that the second-order judgments of these individuals can be affected by NIBS would provide compelling scientific evidence for developing novel intervention protocols that integrate psychotherapy with neurostimulation, thus building up more effective treatments available to physicians and clinical psychologists.

Our results must be taken cautiously, since null findings regarding the effects of NIBS on metacognition may not have been published as often as significant ones, thus leading to a poorness of evidence concerning the clinical population. Eventual unpublished studies might have also affected the output of our work by hindering the detection of a specific stimulation protocol for efficiently manipulating the processing of second-order judgments.

To our knowledge, this is the first systematic review summarizing a widespread amount of NIBS studies on meta-knowledge. Starting from our results, future investigations could also focus on assessing the role of metacognition in influencing other cognitive functions. In this research framework, delay discounting, that is, an element underlying decision-making (Moro, Saccenti, Ferro, et al., 2023), represents a perfect candidate given the possibility of testing such process either invasively in rodents via open-source behavioral apparatus (Moro, Saccenti, Seccia, et al., 2023) or noninvasively among humans through tDCS (Moro, Saccenti, Vergallito, et al., 2023). Further investigations are therefore needed to fill these gaps and elucidate the phenomenon of thinking about thinking.

## DECLARATION OF TRANSPARENCY

The authors, reviewers, and editors affirm that in accordance with the policies set by the *Journal of Neuroscience Research*, this manuscript presents an accurate and transparent account of the study being reported and that all critical details describing the methods and results are present.

## AUTHOR CONTRIBUTIONS

D.S., A.S.M., M.F., and J.L. were involved in conceptualization; D.S. was involved in writing—original draft; D.S. and A.S.M. were involved in supervision writing—review & editing; S.S., A.M., M.F., and J.L. were involved in supervision.

## CONFLICT OF INTEREST STATEMENT

Authors have no conflict of interest to declare.

## PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/jnr.25330>.

## DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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