Continuous Theta Burst Stimulation to the left anterior medial prefrontal cortex influences metacognitive efficiency

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ABSTRACT

The contribution of the prefrontal areas to visual awareness is critical for the Global Neuronal Workspace Theory and higher-order theories of consciousness. The goal of the present study was to test the potential engagement of the anterior medial prefrontal cortex (aMPFC) in visual awareness judgements. We aimed to temporarily influence the neuronal dynamics of the left aMPFC via neuroplasticity-like mechanisms. We used different Theta Burst Stimulation (TBS) protocols in combination with a visual identification task and visual awareness ratings. Either continuous TBS (cTBS), intermittent TBS (iTBS), or sham TBS was applied prior to the experimental paradigm in a within-participant design. Compared with sham TBS, we observed an increase in participants' ability to judge their perception adequately (metacognitive efficiency) following cTBS but not iTBS. The effect was accompanied by lower visual awareness ratings in incorrect responses. No significant differences in the identification task performance were observed. We interpret these results as evidence of the involvement of PFC in the brain network that underlies metacognition. Further, we discuss whether the results of TMS studies on perceptual metacognition can be taken as evidence for PFC involvement in awareness itself.

1. Introduction

One of the commonly discussed issues in consciousness research is whether activity of the posterior part of the brain is sufficient for visual awareness, or whether PFC involvement is also necessary (for the review, see Boly et al., 2017; Koch et al., 2016; Owen and Guta, 2019; Sandberg et al., 2016). There is evidence relating perceptual awareness to late long-range frontoparietal activity. This evidence comes from multiple fMRI studies which registered activity in frontal regions when participants reported being conscious of certain visual stimuli (e.g., Beck et al., 2001; Binder et al., 2017; Lumer et al., 1998; Imamoglu et al., 2014; Lau and Passingham, 2006; for the review, see Dehaene and Changeux, 2011) and some EEG studies (e.g., Salti et al., 2015). The activity of the PFC, including dorsolateral and medial PFC areas, has been suggested to constitute NCC related to conscious access to the con-

tent of perception (Dehaene and Naccache, 2001; Haynes et al., 2005; Imamoglu et al., 2014). Moreover, recent evidence shows that the inferior frontal cortex contributes to resolution of perceptual ambiguities (Weilnhammer et al., 2021). PFC is claimed to be involved in maintaining and broadcasting specific perceptual contents (for a review, see Mashour et al., 2020; Michel and Morales, 2020). Proponents of the Global Neuronal Workspace Theory (Dehaene and Changeux, 2011) and higher-order theories of consciousness (Brown, 2015, 2019; Lau and Rosenthal, 2011; LeDoux and Brown, 2017) predominantly claim that NCC include PFC areas (Michel and Morales, 2020).

Concurrently, the threshold for access to consciousness and introspective ability have been reported to relate to structural features of the aPFC (Allen et al., 2017; Del Cul et al., 2009; Fleming et al., 2010). Similarly, a few fMRI studies have provided evidence of aPFC engagement in metacognition, i.e., knowledge about one's own cognitive processes.

The metacognition measured with perceptual decision confidence ratings correlates with grey matter volume and myelination in the aPFC. However, different studies link it to functionally lateralized lateral or medial areas (Allen et al., 2017; McCurdy et al., 2013; Fleming et al., 2010, 2012). Higher metacognition in a multiple choice question task followed by confidence rating has been associated with decreased left aMPFC activity (Molenberghs et al., 2016) and greater right medial aPFC functional connectivity with other brain regions (Baird et al., 2013). Moreover, the right aPFC has been reported to be functionally involved in the metacognitive aspects of decision-making (Fleming et al., 2012). Higher right aPFC activity has also been linked to better metacognition about short-term recognition memory (Yokoyama et al., 2010), which shows that the aPFC may play a role in metacognition in general, possibly thanks to the functional diversity of its sub-areas (Gilbert et al., 2010).

1.1. Controversy on the role of PFC for visual awareness

While some research showed that the right dlPFC and the left aPFC lesions shift the threshold for reporting stimulus awareness (Colás et al., 2019; Del Cul et al., 2009), other lesion studies on PFC (likely because of different lesion extent) did not (Eslinger and Damasio, 1985; Kozuch, 2014; Tononi and Laureys, 2009; for the review see Boly et al., 2017). Nevertheless, multiple studies investigating visual NCC did not find PFC activity (Grill-Spector et al., 2000; Tse et al., 2005; Williams et al., 2008) to be associated with visual awareness. They claim that visual awareness is associated either with the early activity of the occipital cortex and/or association areas beyond the PFC (for a review, see Koch et al., 2016; Storm et al., 2017; Tononi et al., 2016). The relationship between the P3 wave (believed to have a partly frontal origin) and awareness in some early EEG studies (e.g., Sergent et al., 2005) have been taken as evidence for the role of the PCF in awareness, yet later MEG studies have shown that stimulus awareness is more reliably decoded from occipital than from frontal sources (Andersen et al., 2016; Sandberg et al., 2013). Taken together, these studies thus do not provide strong evidence that the PFC is part of the NCC (for a review, see Förster et al., 2020).

At the same time, neural activity in the PFC might be related to subjective reports but not to awareness of perceptual content. It is claimed that some modulations of PFC activity represent processes that co-occur with or follow stimulus awareness (for a review, see Aru et al., 2012; De Graaf et al., 2012). Therefore, some researchers suggest that results supporting the role of PFC in visual awareness in fact reflect higher-order post-perceptual aspects of visual awareness, like perceptual information maintenance (especially in identification tasks), or planning and execution responses, e.g., report encoding (Andersen et al., 2016; Brascamp et al., 2015; Frassle et al., 2014; Grill-Spector et al., 2000; Pitts et al., 2014; for the review see Storm et al., 2017; Tsuchiya et al., 2015, 2016). However, when defending PFC involvement in awareness formation, researchers point to studies where PFC activity is registered even if a report is not required (Noy et al., 2015; Vidal et al., 2015). A couple of studies that recorded neuronal ensemble activity from the macaque ventrolateral PFC provide similar support (Bellet et al., 2022; Kapoor et al., 2022; see also Panagiotaropoulos et al., 2020). All the aforementioned studies led us to consider whether the PFC is involved in visual awareness per se or in some forms of metacognition or introspection.

1.2. TMS to PFC and visual awareness

As illustrated in the previous sections, neuroimaging has not provided conclusive evidence of whether the PFC has a causal role in stimulus awareness. Therefore, TMS has been used to manipulate processes related to perceptual judgements by targeting the dlPFC. The first evidence that activity in the dlPFC is causally related to changes in conscious perception was provided by Turatto et al. (2004), who employed

10-Hz rTMS while participants were performing a visual change detection task. To date, according to our knowledge, only one offline rTMS study has reported the engagement of the PFC in the formation of visual awareness judgements. This was shown by applying cTBS to the bilateral middle frontal gyrus and testing visual stimuli perception with an identification task combined with visual awareness judgements (Rounis et al., 2010). Compared to the sham, the cTBS resulted in an overall decrease in metacognitive efficiency, i.e., the ability to judge one's own perception accurately (Fleming and Lau, 2014; in studies on consciousness, metacognitive efficiency is typically estimated as a relation between awareness rating and task performance). This effect was accompanied by lower visual awareness ratings in correct responses in the post-cTBS versus the pre-cTBS condition. A replication study did not reproduce these effects (Bor et al., 2017). Interestingly, Rahnev et al. (2016), contrary to their expectations, reported an increase in metacognitive efficiency after cTBS to the right aPFC as compared to the primary somatosensory cortex. Moreover, this effect was also present after cTBS to the right dlPFC. A similar effect was observed after bilateral cTBS to the aPFC and was interpreted as being related to improved associative recognition memory awareness (Ryals et al., 2015). However, a recent study presented a disruption in prospective memory awareness judgements after applying cTBS to the left PFC (Brodmann area 9/10; Carbajal et al., 2019). Taken together, previous studies have not provided consistent evidence to determine the role of the PFC (and especially the aPFC) in the formation of visual awareness judgements.

1.3. Measurement of awareness and metacognition

Where does the inconsistency between the results investigating the role of the PFC in visual awareness judgements come from? Partly, it might result from the measures of awareness employed. Awareness cannot be measured directly, and multiple empirical awareness measures have been proposed so far (Overgaard, 2017). It is considered that objectively detectable stimuli can remain subjectively invisible (at least to some degree). Thus, awareness measures mostly include subjective scales: sometimes perceptual awareness is measured only with a scale (e.g., Christensen et al., 2006), while sometimes it is measured with a combination of an objective task and a scale (e.g., Schwiedrzik et al., 2009). When researchers to measure visual experience use an objective task only, they most often use the term 'visibility' (e.g., Imamoglu et al., 2014). The association between an objective task and a scale is often analysed (Sandberg et al., 2010; Wierzchoń et al., 2014). In this paper, we operationalize visual awareness judgements as reports of stimulus visibility (Lyyra, 2019; Overgaard et al., 2006), which depend on both the processes responsible for generating visual awareness and the processes related to metacognitive efficiency. Following Overgaard and Sandberg, 2012, we consider the latter to be equivalent to introspection.

All variants of higher-order theories state that a higher-order mechanism is necessary for awareness to occur (Michel and Morales, 2020), while some theoretical approaches frame awareness as a first-order mental state (Overgaard and Sandberg, 2012). At the same time, awareness reports are considered to represent a specific type of metacognitive decision, namely an internal decision about the perceptual content (Fleming, 2020; Overgaard and Sandberg, 2012). For these reasons, metacognitive tasks are often used to study perceptual awareness (Bor et al., 2017; Norman and Price, 2015; Rounis et al., 2010). Since the term 'metacognition' refers to cognitive processes that concern other cognitive processes, it can be conceived in two ways in research on visual awareness: as a metacognitive process where a higher-order process represents or operates on a lower-order process, thus allowing some content of visual perception to become consciously perceived (Brown, 2015; Lau, 2019; Lau and Rosenthal, 2011); or as a metacognitive process (judgement of conscious experience) which operates on conscious representation (process responsible for conscious experience, irrespective of whether this representation is considered to be of a higher-order; Fleming, 2020; Overgaard and Sandberg, 2012). Since metacognition is

typically considered a process that we are conscious of engaging in, by referring to metacognitive efficiency in this paper, we refer to a process of metacognitive judgement we are conscious of engaging in and that concerns the process of visual perception (without postulating or negating the presence of representational levels).

To examine the involvement of the aPFC in visual awareness, we conducted a study in which we administered two active and one sham TBS protocols; we expected that the active protocols may exert the opposite influence on cortex excitability level as has been observed for the primary motor cortex (Huang et al., 2005). We stimulated a left aMPFC area that is proposed to be related to metacognitive efficiency (McCurdy et al., 2013; Molenberghs et al., 2016). We then (1) measured the extent to which participants are objectively sensitive to visual information, which is represented by an estimate of performance in an identification task (the contrast of visual stimuli which were used in adaptive staircases); (2) measured visual awareness judgements represented by PAS ratings. PAS is a categorical scale of stimulus awareness measurement introduced by Ramsøy & Overgaard (2004); (3) measured metacognitive efficiency, i.e., participants' ability to differentiate the content of their visual perception, which is represented by a logistic regression estimate, as used in our previous research (Łukowska et al., 2018; Sandberg et al., 2010; Wierzchoń et al., 2014, 2019), and supplemented with meta-d'/d' (M-ratio; Maniscalco and Lau, 2012). M-ratio is a common measure of metacognitive efficiency, in which metacognitive efficiency (operationalized with meta-d') is corrected for objective task sensitivity (operationalized with d'; Fleming and Lau, 2014).

In summary, the goal of this study was to determine whether influencing left aPFC excitability affects reported visual awareness and, if so, whether it is associated with an overall shift in awareness judgements or/and an impact on metacognitive efficiency. Considering the diversity in previous research outcomes, our hypotheses were non-directional. We assumed that a difference in identification task performance should simply indicate a change (not necessarily conscious) in stimulus recognition. Impairment of the processes responsible for visual stimulus experience should lead to lower awareness ratings for both correct and incorrect identification responses. Therefore, (in principle) such impairment would not influence the metacognitive efficiency measure. However, a decrease in metacognitive efficiency should lead to misclassification of the perceptual content, i.e., lower PAS ratings in correct responses and/or higher PAS ratings in incorrect responses. Thus, a difference in the regression estimate and M-ratio that is not accompanied by a difference in identification task performance or overall PAS ratings would imply a difference in metacognitive efficiency.

2. Materials and methods

2.1. Participants

Twenty-four native Danish volunteers with normal or corrected-to-normal vision who fulfilled the criteria for participation in TMS studies (no history of neurological disorders, psychiatric disorders, or head injury etc., as assessed by a safety screening questionnaire) were recruited from the volunteers' database at the center of Functionally Integrative Neuroscience, Aarhus University, Denmark. Prior to the experiment, participants were asked to complete a screening questionnaire regarding their health and safety aspects of TMS and to sign a written informed consent form. Two participants discontinued the study after the first session. One of them reported that the peripheral facial nerves impacted via TMS caused minor pain; another felt weak after a couple of TBS burst pulses applied to the PFC. Another participant reported a headache after receiving the cTBS protocol and quit the study based on medical advice. Twenty-one right-handed participants completed the study (10 males, 7 left-eye dominant, age mean = 23, SD = 2.7, range = 18–27). We determined the sample size based on the number of participants used by Rounis et al. (2010), where the sample was 20 participants (to counterbalance the three TBS protocols, we included 21 participants).

All participants received financial compensation for taking part in the study. The study was approved by the local ethics committee, *De Videnskabsetiske Komitéer for Region Midtjylland*. It was carried out in accordance with the approved guidelines for TMS research (Rossi et al., 2009; Rossini et al., 2015) and adhered to the tenets of the Declaration of Helsinki (Holm, 2013). Before each application of TBS, participants were reminded that they could quit the study at any time without providing a reason.

2.2. Session sequence

The experiment lasted for four days and included four sessions, each performed at the same time of the day and separated by at least four days to reduce the influence of task learning. On the first day, participants received a couple of burst pulses to the aPFC so they could make informed decisions about further participation in the study. Afterwards, individual RMTs were estimated. Next, they received behavioural training to become familiar with the experimental task and provide us with approximate estimates of their performance level. In each of the following three sessions, participants performed a 5-minute block of task training; subsequently, they received one of three different TBS protocols (TBS order was counterbalanced across participants) and completed four 5-minute blocks of the experimental task.

2.3. Behavioral procedure

The task was run on a PC using PsychoPy software (Peirce, 2007). A chinrest and an LCD monitor (1920×1080 resolution, 60-Hz refresh rate) placed 60 cm away from the participants' eyes were used. The task was performed under constant dim lighting conditions. The experiment was conducted in English (but the PAS was presented in Danish).

Participants performed a visual identification task (Fig. 1). At the onset of each trial, a fixation dot was displayed for 500 ms followed by a target Gabor patch presented for 33 ms, tilted left or right. Next, they reported the tilting of the Gabor patch using accordingly labelled 'Z' and 'X' keyboard keys ('L' and 'R'). Finally, participants reported their visual awareness using the PAS as shown in Fig. 2A. They were instructed to report their stimulus awareness according to the PAS description provided in Fig. 2B and to give their response with one of four keys labelled 1–4 and to position the right-hand index finger over the key '1'. The response times for the identification response and the PAS response were unlimited, but participants were instructed to respond as quickly and accurately as possible. Participants could signal finger slips on each trial by pressing the space key (slip trials were excluded from the analysis).

By using two tilt-specific 3-down/1-up unlimited staircases, we kept the identification task performance at 79% throughout the training and experimental sessions, following the assumption that quantifying differences in metacognitive processing requires holding the behavioural performance constant and dissociating the effect of TBS on metacognitive measures from the identification task performance (Rounis et al., 2010). With a step size equal to 0.5%, the stimulus contrast was decreased after three consecutive correct responses, or it was increased after one incorrect response.

The first-day training session started with a displayed instruction and comprised fifteen trials with high stimulus contrast and accuracy feedback (right/wrong), followed by a 10-minute training session with the experimental task, including verbal feedback from the experimenter, and another 10-minute individual training session with no feedback. The experimental sessions started from individual stimulus contrasts, which were established based on the training session's performance, determined for the left and right Gabor patch separately. Similarly to Rounis et al. (2010) and Bor et al. (2017), the staircases were identical for all sessions. Outside of the staircase, after every 15, 20 or 25 trials, a trial with the same high-contrast stimulus was run to prevent participants from changing awareness judgement criteria during the period
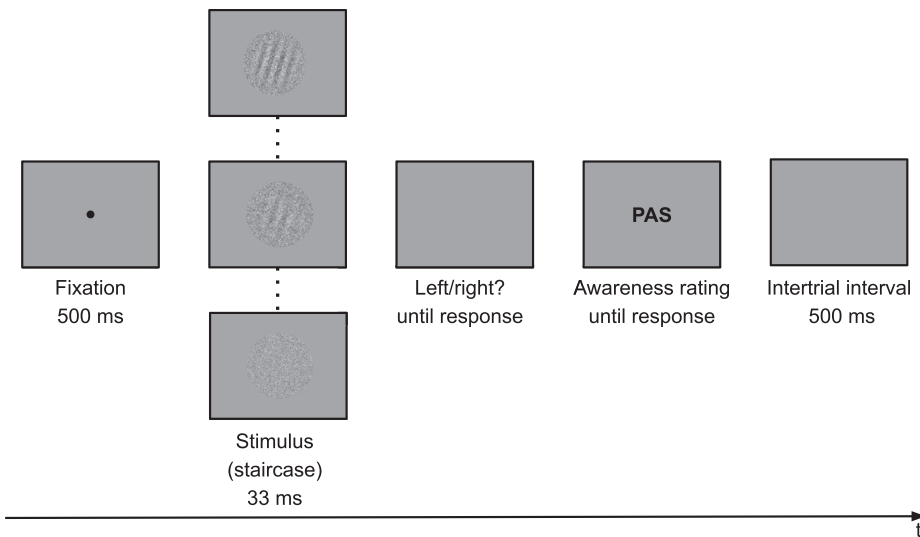
Fig. 1. Schematic illustration of the experimental task. A circular fixation dot (visual angle ∼ 0.5°, presentation time = 500 ms) was presented at the screen centre, followed by a Gabor patch of variable contrast (size = 128×128 pix, visual angle ∼ 3°, spatial frequency ∼ 4 cycles per degree, a standard deviation of the Gaussian envelope = 5 pixels, presentation time = 33 ms, tilted −45° or 45° rotation from vertical angle respectively) embedded in a same-sized circular visual white noise against a grey background, with equal probability and in random order. Participants were required to perform an identification task, i.e., to determine the tilting of the Gabor patch. After each identification response, participants provided a visual awareness rating of stimulus tilting using the PAS. The trials were separated by 500-ms intervals.
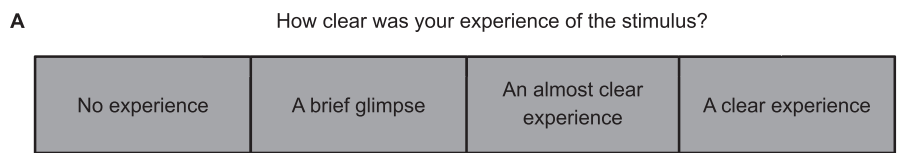
Fig. 2. A) The PAS as presented in every trial. B) The PAS description – an adapted version of the original PAS, published by Ramsoy and Overgaard (2004). This description was provided in the instructions for the pre-training and pre-testing sessions. Following the theoretical position of the authors of the original scale, we treated the PAS as the measure of visual experience, thus we excluded the fragments of the original PAS point definition that referred to confidence.

of the experiment. In each testing session, a 4 min 40-s training block preceded TBS to remind participants of how to perform the tasks. After termination of the stimulation, the participants moved to an adjacent room and commenced the behavioural testing without further delay. Testing thus typically commenced shortly after stimulation and lasted 20 min per condition.

2.4. TMS protocols

During TMS, participants wore earplugs for noise protection. The TBS protocols were delivered with a MagPro X100 stimulator using an MC-B70 Butterfly Coil (with the maximal initial dB/dt of 31 kT/s at the coil surface) for the active stimulation; an MC-Placebo-B70 Butterfly Coil was used for the sham protocol. The TBS protocols had conventional patterns and durations (Huang et al., 2005). The protocols were delivered at 75% of the individual RMT and the average intensity equalled 28% (SD = 3.9) of MSO. The estimation of individual RMT started from applying 40% of MSO single-pulse TMS to the left M1 and adjusting stimulation intensity. It was established at what spot the suprathreshold TMS induced the maximal twitch of the right first dorsal interosseous hand muscle. Then, TMS was delivered until the lowest intensity that resulted in motor-evoked potentials larger than 50 μV peak-to-peak amplitude on five out of ten consecutive trials was reached. The site of stimulation was determined with the Nexstim eXimia NBS 3.2 neuronavigation system using individual structural MRI images with a previously predefined region of interest. The stimulation coordinates were in the anterior medial PFC [−9, 54, 18] in the standard MNI space (Molenberghs et al., 2016); the transformation to individual participant brain space was done using a custom-made MATLAB script. The estimated mean peeling depth

equalled 2.6 cm (SD = 0.15) from the scalp. Throughout the RMT determination procedure and the subsequent application of cTBS, the main axis of the coil was orientated at 45° offset from the PA direction. The TMS pulses were biphasic (∼ 280 μs). The current in the brain was PA-AP at the M1 and AP-PA at the aPFC. The coil was kept tangentially to the scalp, which was ensured by using the neuronavigation system. The TBS protocols were counterbalanced between participants and included three protocols, under which 3-pulse bursts at 50 Hz were applied at 5 Hz. We administered two active TBS protocols: cTBS, in which burst trains were applied continuously for 40 s; and iTBS in which burst trains were applied for 2 s and repeated every 10 s for 192 s. These protocols are conceived to have opposite effects on cortical excitability (Huang et al., 2005). For the sham stimulation, we used an imTBS protocol in which burst trains were applied for 5 s and repeated every 15 s for 110 s. Participants kept their eyes closed during the application of the protocols.

2.5. Calculation

During each post-TBS session, participants completed an average of 452 trials over four blocks (1: 59–152, 2: 73–160, 3: 77–168, 4: 72–165; excluding slips, high stimulus contrast trials from outside of the staircase procedure, and trials for which the contrast estimated by the staircase was 0). The staircase procedure decreased the differences in accuracy between participants to the point where any mixed-effects model with accuracy as a dependant variable did not converge. To confirm that the staircase procedure worked as intended and to compare accuracy between conditions, we fitted a non-hierarchical logistic regression model and used the *glm* function with the binomial family. Due to employment

of the staircase procedure, the identification task performance was estimated with a change in stimulus contrast and identification task RT. To test stimulus contrast distributions, we regressed contrast on the TBS condition and random participant-specific intercepts and random TBS condition effects. To test the differences in rating distributions, we fitted a cumulative link mixed-effects model with the TBS condition as fixed effects, random participant-specific intercepts and random TBS condition effects using the Laplace approximation. To test the differences in RT in both tasks in which the response time was unlimited, we removed trials which exceeded the upper limit of 9 SD. Then we fitted linear mixed-effects regression models with TBS conditions as fixed effects, random participant-specific intercepts and random TBS condition effects. To analyse the metacognitive efficiency, we used a logistic regression model, which is assumed to be the correct model for predicting binary outcomes such as accuracy (Norman and Price, 2015), in which higher estimates indicate higher metacognitive efficiency. The metacognitive efficiency model was based on task accuracy, predicted by the interaction between the TBS condition and PAS rating with participant-specific PAS rating intercepts. To employ this model, the PAS ratings were rescaled to the 0–3 range. To further test the differences in rating distributions depending on the identification task accuracy, we fitted a cumulative link mixed-effects model with fixed and random effects of accuracy, TBS condition and their interaction. The primary analysis of metacognitive efficiency is supplemented by M-ratio analyses. To calculate M-ratios, we used both the code of Maniscalco & Lau (2014) and the HMeta-d model of Fleming (2017). The meta-d' parameter was estimated by finding the d' value that would produce the observed subjective ratings' hit and false alarm rates under the assumption of a metacognitively perfect observer. M-ratio indicates the amount of evidence available for metacognitive judgement relative to the amount of evidence available for an objective (identification task) decision, e.g., an M-ratio value of 0.7 shows that 30% of the sensory evidence available for the objective decisions is lost when metacognitive judgements are made, while a value of 1.3 suggests that more evidence is available for metacognitive judgements than for objective decisions. M-ratio values higher than 1 are considered to be due to processing of stimulus information that follows an identification decision or due to gaining non-perceptual information (Fleming, 2017; Skóra and Wierzchoń, 2016; van den Berg et al., 2016); they might also be due to processing of information that is parallel in time to the identification task decision. We estimated the M-ratios for each TBS condition and each participant separately. Next, we fitted linear models to estimate the difference in each parameter between the sham TMS condition and the active TBS conditions. We calculated M-ratio to be able to compare our results with the results of previous cTBS studies (Bor et al., 2017; Rounis et al., 2010). All presented models were fitted using the R statistical environment (R Core Team, 2019). The mixed-effects regression models were fitted using the *lme4* package (Bates et al., 2015), and the cumulative link mixed-effects models were fitted with the *ordinal* package (Christensen, 2019). For the pairwise comparisons, we used the *emmeans* package, and the p values for pairwise comparisons were adjusted using the Tukey method (Lenth, 2021). The p values were estimated with the *lmerTest* package (Kuznetsova et al., 2017). The generalised linear model was fitted with the *stats* package, which is included in R. We have reported all conditions used and the data exclusions. Perhaps different measures of metacognitive efficiency can be estimated using our data. The data and the script for data cleaning are provided on the Open Science Framework (www.osf.io/3yb2g).

3. Results

All the models that estimated the differences between the conditions for each parameter of interest converged. Consistently with the predictions, the accuracy analysis of the identification task did not reveal any difference between cTBS vs sham, iTBS vs sham, and cTBS vs iTBS (Fig. 3A, Table 1A); this shows that the stimuli contrast-based staircases

Table 1

Between-conditions comparison of regression coefficients for the regression models; cTBS and iTBS compared to sham and cTBS compared to iTBS. A) Results summary of the logistic regression model for the identification task accuracy, with TBS condition as a fixed effect. B) Results summary of the linear mixed-effects regression model for the stimulus contrast, with TBS condition as a fixed effect and random participant-specific intercepts and random TBS condition effects. C) Results summary of the linear mixed-effects model for the identification task reaction time, with TBS condition as a fixed effect; participant-specific TBS condition effect and intercept were used as random effects. D) Results summary of cumulative link mixed-effects model for the PAS ratings with TBS condition as fixed effect; participant-specific TBS condition effect and intercept were used as random effects. E) Results summary of the linear model for the PAS reaction time with TBS condition as a fixed effect; participant-specific TBS condition effect and intercept were used as random effects.

A	Identification task accuracy				
	Predictor	**Estimate**	**Est. Error**	**z value**	**Pr (>|z|)**
	cTBS - sham	−0.04	0.04	−1.14	.254
	iTBS - sham	−0.03	0.04	−0.87	.387
	cTBS - iTBS	−0.01	0.04	−0.27	.787

B	Stimulus contrast					
	Predictor	**Estimate**	**Std. Error**	**df**	**t value**	**Pr (>|t|)**
	cTBS - sham	0.08	0.10	19.85	0.85	.406
	iTBS - sham	0.19	0.10	19.98	1.96	.065.
	cTBS - iTBS	−0.11	0.09	19.99	−1.24	.229

C	Identification task RT (ms)					
	Predictor	**Estimate**	**Std. Error**	**df**	**t value**	**Pr (>|t|)**
	cTBS - sham	−50.56	41.59	19.84	−1.22	.238
	iTBS - sham	−42.42	49.10	19.91	−0.86	.398
	cTBS - iTBS	−8.14	38.56	19.82	−0.21	.835

D	PAS rating				
	Predictor	**Estimate**	**Std. Error**	**z value**	**Pr (>|z|)**
	cTBS - sham	−0.23	0.12	−1.86	.063.
	iTBS - sham	−0.04	0.09	−0.47	.635
	cTBS - iTBS	−0.18	0.12	−1.51	.132

E	PAS rating RT (ms)					
	Predictor	**Estimate**	**Std. Error**	**df**	**t value**	**Pr (>|t|)**
	cTBS - sham	−16.78	18.31	19.72	−0.92	.371
	iTBS - sham	15.60	30.70	19.92	0.51	.617
	cTBS - iTBS	−32.38	27.28	19.91	−1.19	.249

Significance code: . $p < .1$.

on accuracy fulfilled their role. For stimulus contrast, no significant effect was observed for any TBS comparison (Fig. 3B, Table 1B). There was close to significantly higher contrast in the iTBS condition as compared to the sham condition.

Similarly, the analysis of the identification task RT did not show any difference in all the TBS comparisons (Table 1C). The mean identification task RT was 772 ms (SD = 497).

Regarding distribution of PAS ratings, we found that the overall ratings in the cTBS condition were close to significantly lower relative to the sham TBS condition. No difference was observed for the other comparisons (Fig. 4, Table 1D).

The mean PAS rating RT was 398 ms (SD = 393). The analysis of PAS ratings RT did not reveal any difference between the conditions (Table 1E).

Higher metacognitive efficiency was observed in the cTBS compared to the sham TBS, but no difference was found between the iTBS compared to the sham TBS or the cTBS compared to the iTBS (Fig. 5, Table 2A).

We observed a significant interaction between cTBS and accuracy (i.e., correct and incorrect responses; Table 2B).
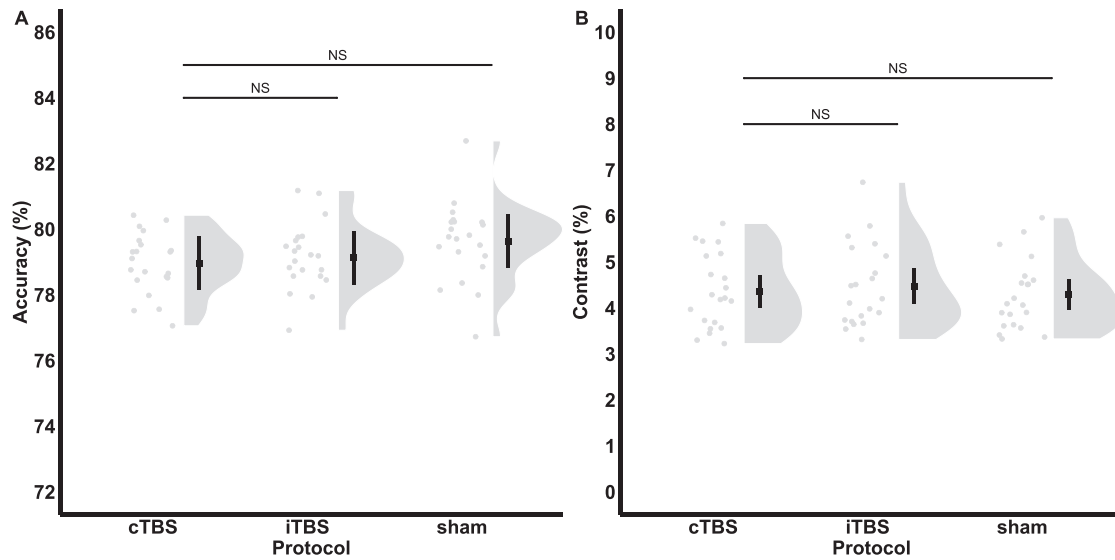
Fig. 3. A) Identification task accuracy (the percent of correct responses) depending on the TBS protocol. B) Stimulus contrast (the percent of computer screen maximum) depending on the TBS protocol. The grey drawings represent individual means and their distributions. The black squares represent estimated means, and the error bars represent 95% CI derived from the models.
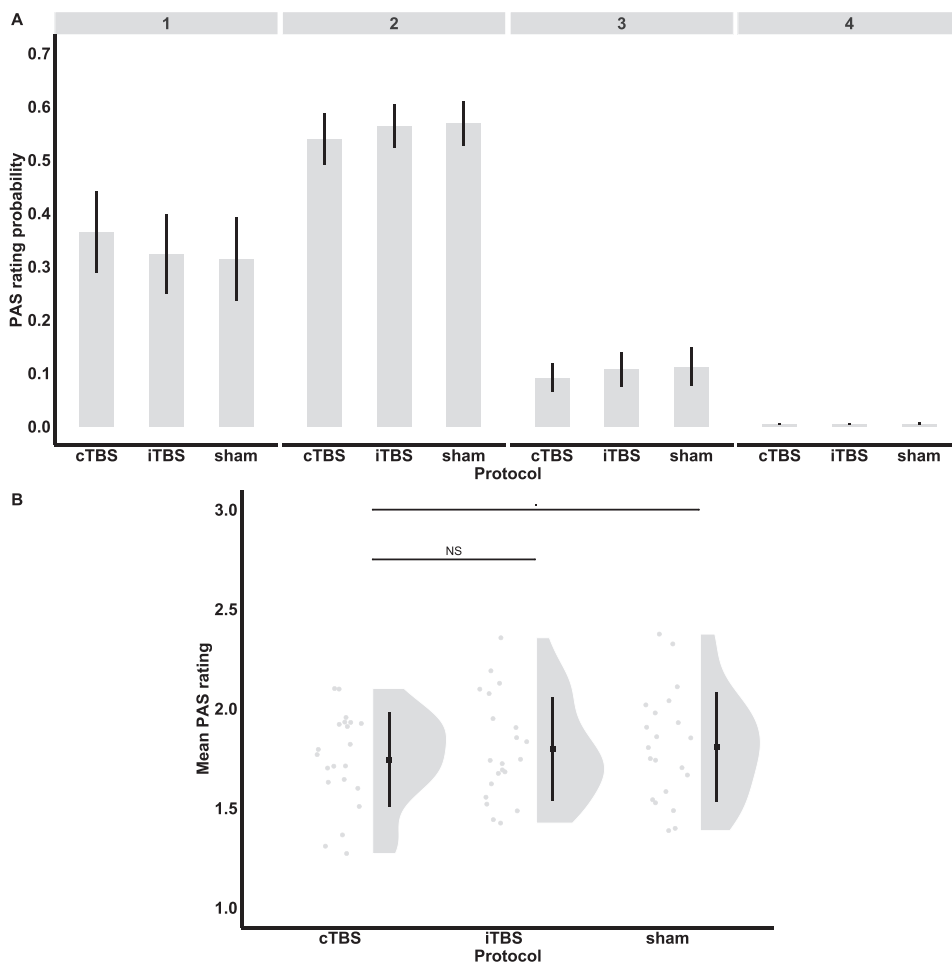

Fig. 4. A) PAS rating probability as depending on the TBS protocol. The grey bars represent estimated means and the error bars represent 95% CI derived from the model. B) Mean PAS rating depending on the TBS protocol. The black squares represent means, and the error bars represent +/- SD. Significance code: . $p <$ .1.
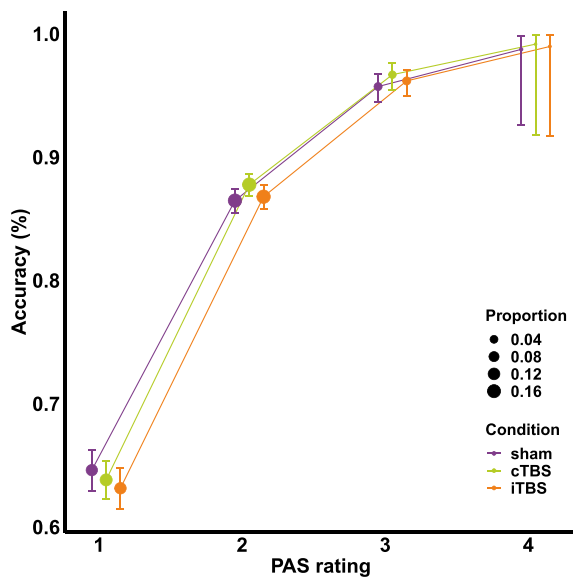
Fig. 5. Model fit for the relationship between decision accuracy and PAS ratings in each TBS condition. The position of filled circles represents the estimated average accuracy for each scale point. The bars represent 95% CI. The size of the dot describes the proportion of each PAS rating, taking into account the total number of trials.

Table 2
A) Results summary of the generalised linear mixed-effects model for the identification task accuracy with an interaction between the fixed effects of TBS condition and PAS rating and a random effect of PAS rating. B) Results summary of the cumulative link mixed-effects model for PAS rating with fixed and random effects of accuracy, TBS condition and their interaction. The basic accuracy condition was incorrect trials. Thus, the intercept concerns PAS rating in incorrect trials.

A	Metacognitive efficiency				
	Predictor	Estimate	Std. Error	z value	Pr (>|z|)
	cTBS - sham	−0.03	0.05	−0.69	.488
	iTBS - sham	−0.06	0.05	−1.26	.208
	cTBS - iTBS	−0.03	0.05	0.60	.551
	cTBS - sham:rating	0.15	0.06	2.38	.017*
	iTBS - sham:rating	0.09	0.06	1.48	.139
	cTBS - iTBS:rating	0.06	0.06	0.94	.350
B	PAS rating: Interaction of TBS condition and identification task accuracy				
	Predictor	Estimate	Std. Error	z value	Pr (>|z|)
	cTBS - sham	−0.46	0.16	−2.93	.003**
	iTBS - sham	−0.11	0.13	−0.80	.424
	cTBS - iTBS	−0.35	0.18	−1.98	.048*
	cTBS - sham:acc1	0.27	0.14	1.99	.047*
	iTBS - sham:acc1	0.09	0.09	0.97	.332
	cTBS - iTBS:acc1	0.18	0.14	1.28	.200

Significance code: * $p < .05$, ** $p < .01$.

Regarding the PAS ratings for incorrect responses, using pairwise comparisons we observed more conservative thus more accurate ratings in the cTBS condition as compared to the sham TBS ($z = −2.93$, $p = .040$; Fig. 6A and C), but not as compared to iTBS ($z = −1.98$, $p = .355$). No effect was observed in the correct responses ($z = −1.42$, $p = .715$ and $z = −1.30$, $p = .786$ respectively; Fig. 6B and D). Taken together, these findings thus indicate that cTBS resulted in a slight increase in metacognitive efficiency compared to sham TBS, and this effect was driven by lower visibility ratings in incorrect trials.

The results of M-ratio comparisons led us to inferences that were comparable to those based on the regression approach. When M-ratio

Table 3
A) Results summary of the M-ratio model fitted with the lmer function to estimate group-level differences. Linear mixed-effects model included TBS protocol as a fixed effect and intercept as a random effect. The M-ratios were calculated using Brian Maniscalco's code. Random effects ($\sigma2 = 0.03$, $\tau00 = 0.05$, $N = 21$, Observations 63). B) Results summary of the M-ratio model fitted with the lmer function to estimate group-level differences. Linear mixed-effects model included TBS protocol as a fixed effect and intercept as a random effect. The M-ratios were calculated using the HMeta-d model. Random effects ($\sigma2 = 0.02$, $\tau00 = 0.03$, $N = 21$ ID, Observations 63).

	M-ratio					
	Predictors	Estimate	Sdt. Error	df	t value	Pr (>|t|)
A	cTBS - sham	0.11	0.05	40.00	2.14	0.039*
	iTBS - sham	0.05	0.05	40.00	0.99	0.327
	cTBS - iTBS	0.06	0.05	40.00	1.15	0.259
B	cTBS - sham	0.09	0.05	40.00	1.83	0.075.
	iTBS - sham	0.07	0.05	40.00	1.34	0.187
	cTBS - iTBS	0.02	0.05	40.00	0.48	0.632

Significance code: . $p < .1$, * $p < .05$.

was estimated with Maniscalco's code (Maniscalco and Lau, 2012), M-ratio was higher in the cTBS condition than in the sham TBS condition ($p = .039$) and no statistically significant difference was found in the other comparisons between conditions (Fig. 7.A, Table 3.A). When M-ratio was estimated based on the HMeta-d model (Fleming, 2017), the difference between the cTBS and sham TBS conditions did not reach statistical significance ($p = .075$; Fig. 7.B, Table 3.B).

4. Discussion

We observed a higher metacognitive efficiency estimate in the cTBS condition as compared to the sham TBS condition, which suggests left aMPFC engagement in processes responsible for metacognitive efficiency. This result is further supported by the observed interaction between the TBS conditions and accuracy related to lower awareness ratings in the incorrect but not in the correct identification task responses in the cTBS condition compared to the sham TBS condition. No evidence was found for differences in the identification task performance, as indicated by the physical stimulus contrast and the identification task RT across TBS conditions. Also, no evidence was found for differences in the PAS RT across TBS conditions. Numerically, both active TBS protocols, when compared to the sham TBS, altered all measures (besides the PAS RT) in the same direction but with different strengths.

Observing an interaction between identification task accuracy and PAS ratings leads us to hypothesise that the detected cTBS effect is related to metacognitive judgement, which relies on performance monitoring. Importantly, the results do not indicate a change in the ability to rate awareness as higher in the correct responses in the cTBS condition. The observation that the cTBS effect on the PAS ratings was limited to incorrect responses suggests it might be attributed to improved error monitoring or integration of error-related information (including metacognitive judgements about the absence of particular stimuli).

Other potential interpretation of our results could be that disruption of particular top-down influences, e.g., disruption of the influence of expectations on perception, could lead to lower PAS ratings in the cTBS condition, specifically on incorrect trials, where bottom-up sensory processing is likely noisy. In this sense, cTBS might have reduced some illusory experiences of the stimulus that was not presented. Another interpretation could be that disruption of typical processing might assign a greater role to expectations. An example of such a case is when a participant expects a stimulus that is different than the one presented and the participant answers incorrectly. The participant might to some degree detect the error and thus rate awareness lower.
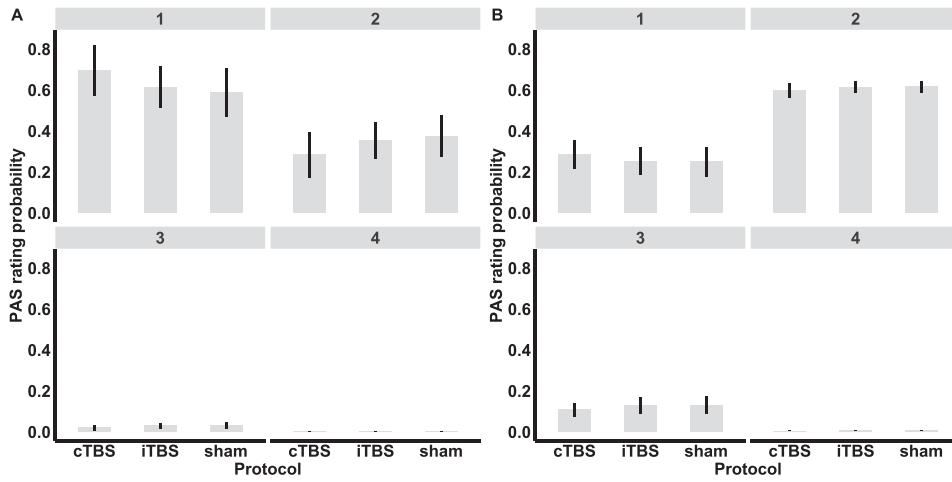
Fig. 6. A) PAS rating probability depending on the TBS protocol on the incorrect responses. The grey bars represent estimated means and the error bars represent 95% CI derived from the model. B) PAS rating probability, depending on the TBS protocol on the correct responses. The grey bars represent estimated means, and the error bars represent 95% CI derived from the model. C) Mean PAS rating depending on the TBS protocol on the incorrect responses. The black squares represent means, and the error bars represent +/- *SD*. D) Mean PAS rating, depending on the TBS protocol on the correct responses. The black squares represent means, and the error bars represent +/- *SD*. Significance code: * $p < .05$.
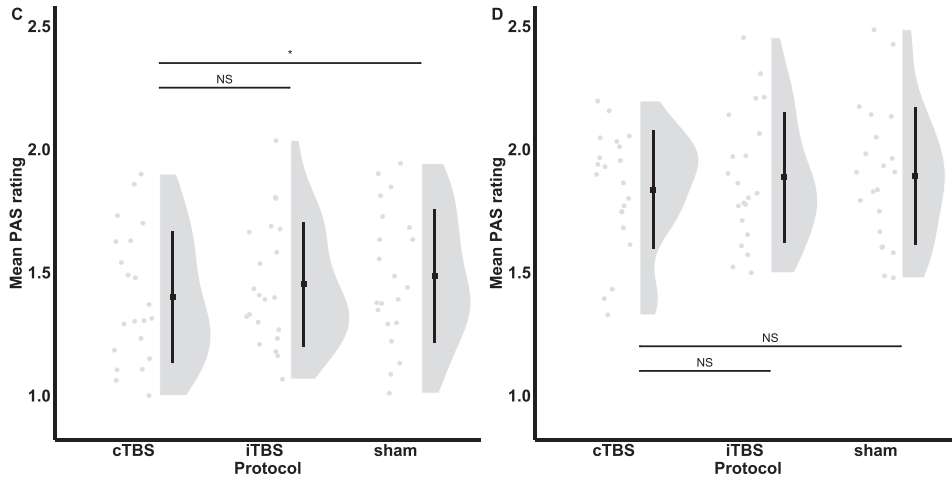

Fig. 7. A) M-ratio depending on the TBS protocol. The M-ratios were calculated using Brian Maniscalco's code. B) M-ratio depending on the TBS protocol. The M-ratios were calculated using the HMeta-d model. The grey drawings represent individual means and their distribution. The error bars represent estimated means with 95% CI derived from the models. Significance code: . $p < .1$, * $p < .05$.
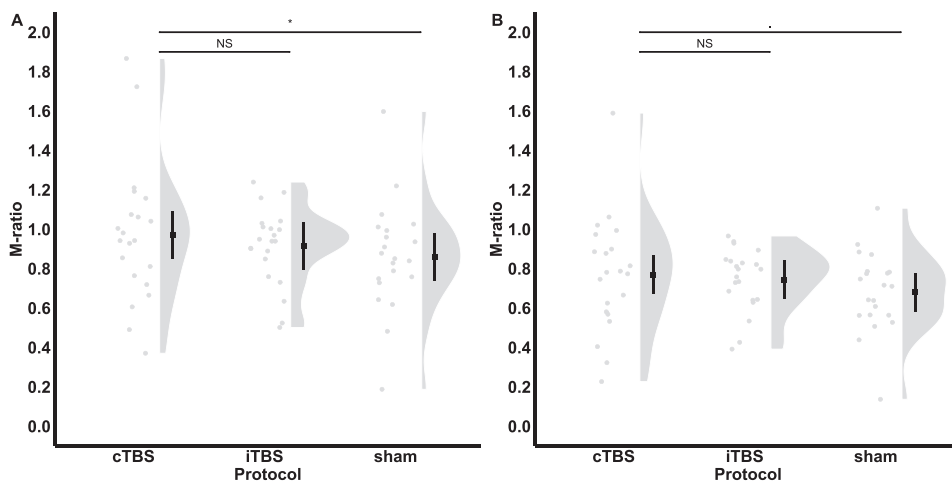
Previous evidence shows that response accuracy influences metacognitive efficiency estimates even when not response confidence but visual awareness judgements are made (Siedlecka et al., 2020; Wokke et al., 2020). While the engagement of posterior brain areas might be necessary to gain awareness about events occurring in an environment, the PFC might particularly specialise in awareness of internal processes, such as the detection of errors, thus influencing awareness ratings. Observing the increase in metacognitive efficiency estimates not accompanied by an increase in PAS ratings in correct responses might suggest there is no unitary process responsible for metacognitive efficiency, but metacognitive efficiency relies on multiple processes, one of which could be the error detection process, which might be influenced individually.

4.1. Comparison to previous research and theoretical considerations

Unlike previous studies, there could be a potential shift (yet not statistically significant) towards a higher stimulus contrast in the iTBS condition as compared to the sham TBS condition; this could occur because of modulation of low-level visual processing or the impairment of decision-making processing that is required in the identification task.

Although performance monitoring may affect response strategy and result in response bias, it cannot be excluded that performing identification tasks as such requires some form of metacognition. Our major result is consistent with that reported by Rahnev et al. (2016), who observed increased metacognitive ability after cTBS to the right aPFC as compared to the primary somatosensory cortex. In contrast to our result, Rounis et al. (2010) observed a decrease in metacognitive efficiency following cTBS to the dlPFC. The effect in the latter study was related to a lower reported level of visual awareness in correct rather than incorrect responses in the post-cTBS condition compared to the pre-cTBS condition (a comparison between the active cTBS and sham cTBS conditions was not reported). This is not in agreement with the results of Rahnev et al. (2016) study, where it was observed that cTBS to the right dlPFC increased metacognitive abilities. The most straightforward explanations of this discrepancy are that aPFC and dlPFC play qualitatively different roles in metacognitive processing, and/or their overall patterns of activity associated with metacognitive efficiency are different. The alternative explanation could be that cTBS to PFC decreases awareness ratings, but the experimental protocols used to date do not make it possible to detect the effect independently of the accuracy. This assumption is inconsistent with the lack of evidence for the cTBS influence on overall confidence ratings reported by Bor et al. (2017) and Rahnev et al. (2016); however, these studies used relatively small samples, i.e., fewer than 20 participants per condition, which is likely not enough to investigate group-level cTBS effects.

Regarding the inconsistency of the results of TBS studies, it is important to note that TBS after-effects may vary depending on the stimulated brain area (Martin et al., 2006), its prior pattern of activity (Gentner et al., 2008), and stimulation parameters, such as current direction (Talelli et al., 2007), intensity (Bohning et al., 1999), and protocol length (Gamboa et al., 2010; Gentner et al., 2008), all of which were different in the mentioned studies, possibly leading to different cTBS outcomes at the neuronal level. Moreover, all cTBS studies included different objective tasks and subjective assessment scales. Using different types of metacognitive ratings can result in the investigation of phenomena with overlapping but distinct qualities (see e.g., Overgaard and Sandberg, 2012). While Rahnev et al. (2016) and Bor et al. (2017) collected response confidence ratings that are to some extent based on non-perceptual information, like action-specific feedback (Fleming et al., 2015) or error monitoring (Yeung and Summerfield, 2014, 2012), Rounis et al. (2010) used visual awareness ratings in their study. On the one hand, if an investigated effect concerns an impact on subjective visibility, awareness ratings measure this effect with more sensitivity than confidence ratings, which suggests that cTBS in previous studies could influence subjective visibility rather than confidence and thus could impact metacognitive ability estimates. On the other hand, cTBS in our study could lead participants to consider awareness judgement to resemble response confidence judgement, therefore the incorrect responses were more often accompanied by lower metacognitive ratings.

Based on the reported pattern of results, we consider it more probable that the cTBS effect on metacognitive efficiency estimates in our study stems from impairment in the ability to judge one's own visual experience, rather than subjective visibility impairment. However, it should be also noted that the observed TMS effects on metacognitive efficiency estimates in cTBS studies may be consequences of the direct or indirect influence of cTBS on processes that directly influence metacognitive judgement, such as criterion setting, overall confidence or impulsivity or other cognitive processes, including expectations, attention, working memory, retrospective memory, and self-related processing, which might in turn influence metacognitive ratings.

Research shows that PFC lesions may affect metacognitive efficiency when judging response confidence (Fleming et al., 2014), but there is also support for the presence of a cognitive control organisation gradient in PFC (Azuar et al., 2014; Badre et al., 2009). Rahnev and colleagues proposed that the caudal, middle and rostral areas of PFC contribute

differently to perceptual decision-making, which reflects on the progressively later stages of this process, i.e., selection, criterion setting, and evaluation, respectively (Rahnev et al., 2016; Shekhar and Rahnev, 2018). It is assumed that dlPFC evaluates how much information is available for stimulus identification decisions when a participant performs the objective task, while aPFC plays an integrative role and its activity increases along with the reliability of participant's confidence judgements (Morales et al., 2018; Fleming et al., 2012; Yokoyama et al., 2010).

The lower awareness ratings might be interpreted as decreased conscious access to lower levels of perceptual processing; however, in principle they could also be related to a change in participants' definition of what constitutes a particular level of perceptual awareness (i.e., depend on an introspective decision criterion rather than a perceptual change) and/or relate to the overall confidence level. Although neuronal representation of confidence in the perceptual decision has been linked to the ventral striatum (Hebart et al., 2016), dlPFC activity correlates with reported confidence (Fleck et al., 2006; Morales et al., 2018).

Targeting the dlPFC with TMS has been reported to influence the level of confidence and/or metacognitive efficiency (Chiang et al., 2014; Rahnev et al., 2016; Rounis et al., 2010; Shekhar and Rahnev, 2018). In a study by Shekhar and Rahnev (2018), single-pulse TMS to the dlPFC decreased reported confidence, whereas when applied to the aPFC it increased metacognitive efficiency (these effects were observed for the second half of the experimental trials only). Therefore, it might be that the effects of cTBS on visual awareness ratings in Rounis et al. (2010) and our study stem from influences on confidence, which played a role in the observed cTBS effects on metacognitive efficiency estimates via lowering the metacognitive ratings in either correct or incorrect trials. Future studies should address whether the effects rely on changes in metacognitive efficiency or the use of more conservative criteria (metacognitive bias).

Theoretically, a difference in visual awareness or in the criteria for reporting certain levels of awareness may result in a difference being observed in metacognitive efficiency measures (Rausch and Zehetleitner, 2017). For example, in our study it could be a shift in the criterion for reporting a brief glimpse of a stimulus, resulting in lower PAS ratings (because the cTBS effect on PAS ratings was limited to incorrect trials, and low visibility experience accompanies the incorrect responses more than the correct responses). While we do not exclude that criteria shifts may be reasons for reporting lower metacognitive ability in Rounis et al. (2010) and/or observing the cTBS effect on metacognitive efficiency in our study, this explanation might be less likely than the change in metacognitive efficiency. An argument for the latter is that neither Bor et al. (2017) nor Rahnev et al. (2016), who both employed cTBS, found an effect on confidence ratings, whereas an impact on metacognitive efficiency was found in both Rounis et al. (2010) and Rahnev et al. (2016) despite the different types of the metacognitive judgements used. We further partly supported our conclusion by presenting the results of analyses of M-ratio, which is considered to be one of the most bias-independent methods for measuring metacognition (Fleming et al., 2014).

Since unilateral PFC lesions can cause top-down attention and memory deficits, another issue concerns disentangling perceptual awareness and metacognition from these processes (Voytek et al., 2010). Attention shares neural underpinnings with processes often defined as metacognition or awareness (Fernandez-Duque et al., 2000; for the review, see Lamme, 2020). On the one hand, participants in the studies of Rounis et al. (2010) and Bor et al. (2017) had to attend selectively to one of two peripheral stimuli, therefore the effects of dlPFC stimulation might have been associated with a disturbance of attention that mediated the influence on metacognitive efficacy. Moreover, due to the adjacent location of the dlPFC and the aPFC and the anatomical and functional connections between these areas (Azuar et al., 2014; Badre et al., 2009), some additional direct or indirect TMS influences might be considered. At the same time, it is known that cTBS to dlPFC can influ-

ence working memory (Schicktanz et al., 2015; Vékony et al., 2018). Given the fact that the identification decision and visual awareness judgement were provided simultaneously and were included a relative judgement in Rounis et al. (2010) study (and for this reason, required a high level of working memory resources), it may be hypothesised that cTBS decreased working memory capacity rather than metacognitive efficiency. However, in our study, stimuli were presented singly in the centre of the screen, and objective and subjective responses were separated; therefore, we can consider this explanation less likely. While our study attempted to account for individual differences in seeing left- and right-orientated Gabor patches, we cannot exclude that including separate staircases for both Gabor patches impacted response strategies. In sum, we observed an effect that is consistent with some of the previous research; however, because of the issues discussed above, the results of studies investigating the impact of TBS to PFC on visual awareness should be interpreted with caution and followed up in larger samples.

4.2. Implications for theories of consciousness

One might infer that the results of our study provide support for the Higher-Order Thought Theory (Lau and Rosenthal, 2011) or the Global Neuronal Workspace Theory (Dehaene and Naccache, 2001; Dehaene, 2014), but our results do not support theories such as the Recurrent Processing Theory, which does not hold the assumption that NCC includes PFC (Lamme, 2020), or the Integrated Information Theory, which argues that PFC connectivity patterns are not suited to integrating information and thus are not important for awareness formation (Tononi et al., 2016). However, we are reluctant to make such far-reaching conclusions. The observation that PFC activity influences metacognitive efficiency does not imply that PFC is necessary for certain conscious content to occur. A recent synthesis of research analysing outcomes of studies in which intracranial electrical stimulation to the PFC was employed suggests no evidence for reliable alternations in perceptual awareness following PFC stimulation (Raccah et al., 2021). This is inconsistent with the predictions of some higher-order theories and some developments of Global Workspace Theory. On the one hand, this does not imply that stimulation to PFC cannot influence perceptual awareness in a way that is not noticeable or reportable by participants or can be observed only under specific task conditions (for the commentary articles to Raccah et al., 2021, see Baars et al., 2021 and Naccache et al., 2021). On the other hand, participants' ability to differentiate spontaneous fluctuations in conscious experience from other effects elicited by neuromodulation techniques could limit the reliability of some brain stimulation research (Fox and Parvizi, 2021).

The conflicting conclusions concerning the role of PFC in consciousness found in the scientific literature might stem from different understandings of the terms 'visual consciousness' or 'visual awareness', e.g., whether confidence or working memory-related processes are assumed to constitute visual awareness. Although perceptual content has been decoded above chance level from PFC activity in various experiments (for a review, see Odegaard et al., 2017), awareness-related PFC activity might not represent any specific perceptual content. The PFC's role in consciousness might be limited to processes that influence overall conscious experience or to stimulus awareness judgement. Currently, no method allows response criteria or overall confidence to be disentangled from stimulus awareness itself. Thus, we cannot exclude that differences observed in awareness ratings are caused by judgement bias. However, the confidence with which we perceive a stimulus is often considered to be a component of the conscious experience of this stimulus. Some researchers argue that representations in the global workspace always carry with them an estimate of confidence (Kouider et al., 2010; Shea and Frith, 2019) or involve a feeling of knowing (Baars et al., 2021). Thus, confidence might be treated as a component of visual awareness (Lau and Rosenthal, 2011). Currently, explaining the relationship between perceptual metacognition and perceptual awareness

is considered one of the key goals for the field of visual metacognition research (Rahnev et al., 2021).

4.3. Methodological considerations and future directions

Even though we demonstrated that cTBS to the aMPFC increases estimates of metacognitive efficiency, which supports the role of the PFC in the assessment of subjective experience, there is not yet conclusive evidence that this effect stems from a change in PFC excitability. There are two probable but overlooked sources of confounds in TMS studies that investigate near-threshold perception. The first is peripheral nerve stimulation, which might influence vigilance and in consequence influence factors related to metacognitive judgement. The second source is the potential change in retinal activity, which might influence visual perception. An alternative explanation for lower PAS ratings in incorrect responses in the cTBS condition is that stimulation to the PFC results in an electric current passing through the eyeballs, thus influencing retinal activity and, in consequence, impairing visual processing. This might not be specific to aPFC stimulation; for example, Webster & Ro (2017) suggest that phosphenes (simple visual sensations, often in the form of light spots) that are perceived as a result of TMS to areas as far from the retina as the vertex or parietal cortex may arise from retinal stimulation. However, if influencing vigilance level or retinal stimulation were the case, likely it would cause a difference in identification task performance, but we did not observe this in the cTBS or the sham comparison. Nonetheless, objective tasks are less sensitive to detecting subtle changes in visual awareness compared to subjective awareness ratings (Sandberg et al., 2010), and performing an objective task is more automatic than providing subjective assessment, thus it might not require the engagement of the aPFC. Nevertheless, in this context, it is worth noting that the psychometric function for PAS has a shallower slope than that for accuracy (Sandberg et al., 2011), which suggests that identification task performance should be more affected than PAS ratings by the same external influence on visual processing.

It is important to note that cTBS was never significantly different from iTBS in all analyses. The reason for this could be related to suboptimal iTBS parameters, iTBS inefficacy in a particular area, or participants' individual differences, which affected the overall iTBS efficacy. Previous research that included multiple measures of cognitive functions reported only a minor impact of iTBS to PFC areas (Grossheinrich et al., 2009). Another explanation is that iTBS's impact on the discrimination task was high enough to balance the potential iTBS impact on PAS ratings by (insignificantly from the statistical perspective) increasing the contrast of presented stimuli. Also, similarly to some previous TBS studies, we do not find support for conceiving cTBS and iTBS as protocols that always have the opposite behavioural consequences (Grossheinrich et al., 2009; Hamada et al., 2013; Viejo-Sobera et al., 2017). This is in line with evidence that the typical excitatory and inhibitory outcomes of different TBS protocols applied to M1 might not be transferable to PFC. While some studies have provided evidence for the efficiency of cTBS to PFC in modulating cognitive performance, a couple of studies involving both cTBS and iTBS to PFC showed no differences between cTBS and iTBS effects, or they observed differences only in certain tasks (for the meta-analysis of PFC TBS influence on executive functions, see Lowe et al., 2018). Molenberghs et al. (2016) observations that metacognitive ability was inversely related to aMPFC activity, and that cTBS in our study led to higher metacognitive efficiency estimates, point towards the overall inhibitory influence of cTBS in our study. Future studies employing cTBS to influence awareness could combine it with neuroimaging to examine cTBS effects at the brain level.

Future research might disentangle the extent of PFC contribution to the content of consciousness from its contribution to the level of wakefulness; it might also clarify the role of different subcomponents of PFC in shaping awareness judgement. Especially, there is a need to distinguish between the correlates of content directly related to stimulus, non-perceptual content, and post-perceptual content of awareness,

as well as to consider potential PFC involvement in decisions about the absence of stimulus (Anzulewicz et al., 2019; Fleming, 2020). These additional steps could focus on dissociating stimulus awareness from other cognitive processes, and on determining to what degree metacognitive processes are lateralized. Future studies may also address the problem of whether TMS primarily affects confidence or visual awareness by employing both measures at once and/or including above-threshold stimuli combined with confidence ratings. There is also a need to clarify whether alterations in metacognitive efficiency accompanying brain stimulation to aMPFC does not result from the direct (due to the spread of electric field) or indirect (via network effects) influence on the activity of other brain areas, like posterior medial frontal cortex, which is likely involved in error monitoring (Dehaene et al., 1994; Gehring et al., 1993). Since MPFC receives visual information from the superior temporal cortex (Kondo, Saleem & Price, 2003, 2005), it also seems compelling to investigate communication between PFC and the temporal lobe.

Importantly, the issue concerning the difference between metacognition and awareness is closely related to how conscious experience is operationalised within different theories of consciousness. It may further be noted that the observed effect sizes were not large, thus caution is required when interpreting the results. Considering the differences in findings across all studies to date on metacognition that included TBS to PFC, PFC engagement in perceptual awareness needs further investigation, and we look forward to future attempts to investigate this issue with the use of better stimulation techniques, larger samples, and behavioural paradigms allowing better differentiation between metacognitive efficiency and visual awareness to address the concerns that have been raised in this article.

5. Conclusion

Summing up, our study indicates that the left aMPFC is involved in processes related to metacognitive efficiency, but its involvement in the overall level of reported visual awareness remains inconclusive. While the results of our study specifically support the claim that PFC activity affects the assessment of visual awareness, it does not explicitly support or exclude the possibility that PFC is necessary for the conscious experience of stimulus. The cTBS effect was related to a decrease of awareness in incorrect trials, which points towards an effect on metacognition effect rather than stimulus awareness. Additionally, we did not find evidence supporting the hypothesis that cTBS and iTBS exert opposite effects.

Declaration of Competing Interest

Credit authorship contribution statement

Justyna Hobot: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Zuzanna Skóra:** Methodology, Software, Resources, Writing – review & editing. **Michał Wierzchoń:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Kristian Sandberg:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

The data and scripts for running the statistical analysis are publicly available at www.osf.io/3yb2g.

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