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REVIEW ARTICLE

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Can non-invasive brain stimulation modulate peak alpha frequency in the human brain? A systematic review and meta-analysis

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Abstract

Peak alpha frequency (PAF), the dominant oscillatory frequency within the alpha range (8–12 Hz), is associated with cognitive function and several neurological conditions, including chronic pain. Manipulating PAF could offer valuable insight into the relationship between PAF and various functions and conditions, potentially providing new treatment avenues. This systematic review aimed to comprehensively synthesise effects of non-invasive brain stimulation (NIBS) on PAF speed. Relevant studies assessing PAF pre- and post-NIBS in healthy adults were identified through systematic searches of electronic databases (Embase, PubMed, PsychINFO, Scopus, The Cochrane Library) and trial registers. The Cochrane risk-of-bias tool was employed for assessing study quality. Quantitative analysis was conducted through pairwise meta-analysis when possible; otherwise, qualitative synthesis was performed. The review protocol was registered with PROSPERO (CRD42020190512) and the Open Science Framework (https://osf.io/2yaxz/). Eleven NIBS studies were included, all with a low risk-of-bias, comprising seven transcranial alternating

Abbreviation list: AG, Angular gyrus; CES, Cranial electrotherapy stimulation; CI, Confidence interval; COBIDAS, Committee on Best Practice in Data Analysis and Sharing; CoG, Centre of gravity; DLPFC, Dorsal lateral prefrontal cortex; EEG, Electroencephalography; FEF, Frontal eye fields; FFT, Fast Fourier transform; IAF, Individual alpha frequency; ICA, Independent component analysis; IPS, Intraparietal sulcus; ITPC, Inter-trail phase coherence; LTD, Long-term depression; LTP, Long-term potentiation; mA, Milliamps; MD, Mean difference; MEEG, Magnetoencephalography and electroencephalography; MEG, Magnetoencephalography; MRI, Magnetic resonance imaging; MT, Motor threshold; NIBS, Non-invasive brain stimulation; OSF, Open Science Framework; otDCS, Oscillatory transcranial direct current stimulation; PAF, Peak alpha frequency; PICO, Participant, intervention, control, outcome; PRISMA, Preferred Reporting Items for Systematic Review and Meta-Analyses; PROSPERO, International Prospective Register of Systematic Reviews; RINCE, Reduced impedance non-invasive cortical electrostimulation; rTMS, Repetitive transcranial magnetic stimulation; SE, Standard error; SM, Sensorimotor; STDP, Spike-timing dependent plasticity; SWiM, Synthesis Without Meta-analysis; tACS, Transcranial alternating current stimulation; TBS, Theta burst stimulation; tDCS, Transcranial direct current stimulation; tES, Transcranial electrical stimulation; TMS, Transcranial magnetic stimulation; tRNS, Transcranial random noise stimulation.

For affiliations refer to page 15

current stimulation (tACS), three repetitive transcranial magnetic stimulation (rTMS), and one transcranial direct current stimulation (tDCS) study. Meta-analysis of active tACS conditions (eight conditions from five studies) revealed no significant effects on PAF (mean difference [MD] = −0.12, 95% CI = −0.32 to 0.08, $p = 0.24$). Qualitative synthesis provided no evidence that tDCS altered PAF and moderate evidence for transient increases in PAF with 10 Hz rTMS. However, it is crucial to note that small sample sizes were used, there was substantial variation in stimulation protocols, and most studies did not specifically target PAF alteration. Further studies are needed to determine NIBS's potential for modulating PAF.

KEYWORDS
brain stimulation, dominant alpha frequency, electrical stimulation, individual alpha frequency, magnetic stimulation

1 | INTRODUCTION

Alpha is the dominant oscillatory frequency (8–12 Hz) recorded in the human brain using electroencephalography (EEG) or magnetoencephalography (MEG) (Van Diepen et al., 2019). The frequency exhibiting the highest power within the alpha range, termed the peak alpha frequency (PAF) or individual alpha frequency (IAF), is relatively stable within individuals (Kondacs & Szabó, 1999) and possesses a trait-like quality, with heritability accounting for a significant portion (71–83%) of the variance in PAF across individuals (Posthuma et al., 2001). Faster PAF (i.e., higher frequency) is associated with improved cognitive performance in working and semantic memory tasks (Klimesch, 1999). PAF is also correlated with individual processing capacity, both in trait (i.e., inter-individual) and state (i.e., intra-individual) contexts (Minami & Amano, 2017). PAF follows a developmental trajectory, increasing throughout childhood, stabilising in late-adolescence/adulthood (∼10 Hz), and decreasing in old age, effectively paralleling age-related changes in brain volume and cognitive performance (Bigler et al., 1995; Breslau et al., 1989).

Individuals with depression (Tement et al., 2016), post-traumatic stress disorder (Wahbeh & Oken, 2013), autism (Dickinson et al., 2018), and chronic pain (Fauchon et al., 2022; Kim et al., 2019; Sarnthein et al., 2006; de Vries et al., 2013) exhibit slower PAF than the general population. Interventions that can modulate PAF may be useful to help illuminate the role of oscillations for brain function in health and disease and potentially underpin new therapeutic approaches for a variety of conditions (Herrmann et al., 2013; Sejnowski & Paulsen, 2006). A number of interventions are thought to be capable of modulating brain oscillations, including non-invasive brain stimulation (NIBS).

NIBS techniques, such as transcranial magnetic stimulation (TMS) and transcranial electrical stimulation (tES), are a collection of safe technologies for exploring and modifying brain activity without requiring invasive procedures (Herrmann et al., 2013; Ridding & Rothwell, 2007). TMS applies a magnetic field via a coil to induce electrical currents in the brain tissue below, while tES delivers weak electrical currents to the scalp (Herrmann et al., 2013; Ridding & Rothwell, 2007). Both techniques interact with electrical fields produced by neural populations in the brain, thus modulating synaptic activity and potentially leading to changes in brain oscillations, such as PAF (Bergmann & Hartwigsen, 2021; Braga et al., 2021; Herrmann et al., 2013; Mansouri et al., 2018; Vogeti et al., 2022). The mechanisms by which these changes occur are not completely established, but two possibilities include entrainment and the modulation of neural plasticity (Vosskuhl et al., 2018).

Entrainment theory suggests that internal brain oscillations synchronise with external rhythmic inputs (Lakatos et al., 2019; Thut, Schyns, & Gross, 2011). For instance, repetitive TMS (rTMS) and some tES methods, such as oscillatory transcranial direct current stimulation (otDCS) and transcranial alternating current stimulation (tACS), rhythmically alter synaptic firing or thresholds, potentially synchronising internal oscillations to ongoing external input (Braga et al., 2021; Mansouri et al., 2018; Thut, Schyns, & Gross, 2011). However, as entrainment effects are theoretically only expected to outlast stimulation cessation by a few cycles (Thut, Schyns, &

Gross, 2011), longer lasting effects may rely on neural plasticity, such as spike-timing dependent plasticity (STDP) (Polanía et al., 2018; Vosskuhl et al., 2018; Zaehle et al., 2010). In STDP, the timing of neuronal firing influences the strength and direction of synaptic connections, with action potentials arriving shortly before a post-synaptic potential leading to long-term-potentiation (LTP) and those arriving shortly after leading to long-term-depression (LTD) (Markram et al., 1997; Zaehle et al., 2010). The resulting changes in excitation and inhibition balance and firing patterns may be visible by changes in EEG oscillatory activity. The effect of NIBS techniques that lack a rhythmic component, but still influence patterns of neuronal firing, such as the constant currents applied by tDCS or irregular currents by transcranial random noise stimulation (tRNS), may also be explained by STDP (Bindman et al., 1962; Purpura & McMurtry, 1965).

PAF represents the dominant frequency of brain oscillations, and oscillations reflect fluctuations in the electrical activity of neural populations over time (Biasiucci et al., 2019; Cohen, 2017a; Lopes da Silva, 2013, 2023; Nunez & Srinivasan, 2006). Therefore, notwithstanding the precise mechanisms involved, if NIBS techniques can alter the electrical activity of neural populations (Bergmann & Hartwigsen, 2021; Braga et al., 2021; Herrmann et al., 2013, 2016; Mansouri et al., 2018; Polanía et al., 2018; Vogeti et al., 2022), then NIBS techniques are prime candidates for PAF modulation. Literature provides evidence that NIBS techniques can alter the magnitude of alpha oscillations and increase the phase coherence of ongoing oscillations (Bergmann & Hartwigsen, 2021; Herrmann et al., 2013; Vogeti et al., 2022), but it remains unclear if these effects directly correspond to changes in resting state PAF that outlast the stimulation duration. As PAF is closely associated with various cognitive functions and diseases, if we find that NIBS interventions are also able to modulate the frequency of alpha oscillations (i.e., PAF), then we will gain a new approach for influencing and investigating brain function. However, the existing literature lacks a systematic review of NIBS effects on PAF to guide such investigations.

The aim of this systematic review was to comprehensively synthesise the evidence for general and specific effects of different NIBS interventions on PAF in healthy participants. Specifically, we aimed to determine: 1) the types of NIBS interventions used to modulate resting state PAF in healthy adults; 2) the magnitude, direction, and duration of any effects of NIBS on PAF; and 3) the sample sizes, methodological approaches, and environmental characteristics of studies that successfully modulated PAF.

2 | MATERIALS AND METHODS

2.1 | Protocol and registration

This systematic review was reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Liberati et al., 2009; Moher et al., 2009). The protocol of this review was registered at the International Prospective Register of Systematic Reviews (PROSPERO; registration number: CRD42020190512) and has been made available on the Open Science Framework (OSF; https://osf.io/2yaxz/). Note that the initial protocol sought to explore the effect of a range of different interventions (e.g., NIBS, exercise, drugs) on PAF. Because of the heterogenous mechanisms of action and wide variety of interventions used to modulate PAF, this study only reports the effects of NIBS interventions. This protocol deviation was recorded on OSF (https://osf.io/2yaxz/).

2.2 | Search strategy

Searches were conducted to find completed studies since 2000 in the following databases: EMBASE, PsychINFO, PubMed, Scopus, and the Cochrane Library. Search terms consisted of combinations of key terms referring to PAF, EEG, and neuromodulation interventions, using boolean operators and truncations to ensure sensitivity and specificity. The project team created exact search strategies with guidance from an expert librarian and adapted them for each database (Supplementary Material 1).

Trial registers and repositories of results, including the U.S. National Library of Medicine (https://clinicaltrials.gov/), the System for Information on Grey Literature in Europe (https://opengrey.eu/), the New York Academy of Medicine Grey Literature Report (http://www.greylit.org), and the Open Science Framework Preprint archive search (https://osf.io/preprints/discover) were searched to identify completed unpublished studies.

Database searches were carried out by the first author (SKM). The initial search, including all neuromodulation techniques, was conducted in February 2021, and a final repeat search of only NIBS interventions was conducted in April 2023 prior to publication of review outcomes. References of relevant articles and reviews were also searched manually for additional articles.

2.3 | Inclusion criteria

1. Studies written in English;
2. Studies published after or in the year 2000;

3. Participants: healthy adults aged between 18 and 65 years, no restrictions on sex, gender, or race/ethnicity. Studies involving clinical populations that also assessed a healthy control group were included. Only information from the healthy control group was extracted;
4. Intervention: any intervention using NIBS techniques, including:
   a. magnetic stimulation techniques (e.g., repetitive transcranial magnetic stimulation [rTMS], theta burst stimulation [TBS]),
   b. electrical stimulation techniques (e.g., transcranial alternating current stimulation [tACS], transcranial direct current stimulation [tDCS], cranial electrotherapy stimulation [CES], reduced impedance non-invasive cortical electrostimulation [RINCE], or transcranial random noise stimulation [tRNS]);
5. Comparison: studies with or without control groups were included;
6. Outcome: change in resting state PAF (Hz), with PAF measured using resting state EEG or MEG before and after an intervention. Resting state may include a relaxed supine, seated, or standing position with eyes either opened or closed;
7. Study design: original experimental or quasi-experimental research studies, using single group, parallel, or cross-over study designs with both randomised and nonrandomised allocation.

2.4 | Exclusion criteria

1. Studies investigating patient populations (i.e., defined as registered to receive or receiving medical treatment) without a healthy control group;
2. Studies investigating populations other than humans (i.e., animal models, simulations, computer models);
3. Studies measuring EEG or MEG in a state other than conscious awake states (e.g., sleep, coma, unresponsive wakefulness syndrome);
4. Studies only measuring PAF at one time point or during stimulation;
5. Reviews, commentaries, editorials, study protocols, conference abstracts or proceedings, book chapters, letters to the editor, or case studies.

2.5 | Study selection

Search results were exported to Mendeley version 1.19 (London, UK), where duplicate articles were identified and removed. Two independent reviewers assessed titles and abstracts to identify potentially relevant studies. Any cases of doubt were automatically selected for full-text eligibility evaluation. The full-texts of these studies were retrieved and an automatic full-text scan phase was used to identify articles that reported measurement of PAF in the full text. A conceptual flow chart, key words, and the Python code used for the FT-scan are freely available (https://github.com/sammymillard/ft-scan). Full-texts were assessed by two independent reviewers against eligibility criteria. A third reviewer was consulted to resolve any disagreements. Excluded studies and the reason for exclusion were recorded.

2.6 | Data extraction

A customised data extraction form was used by two independent reviewers to extract data from each relevant study. Any inconsistencies were resolved by a third reviewer. The following data were extracted:

- Study characteristics: study design, randomisation procedures, and number of conditions/groups in each experiment.
- Participant characteristics: sample size, sex, age, and any other demographic information provided.
- Interventions: exact NIBS intervention implemented, route of delivery, dose, duration, frequency, timing of intervention, as well as comparison conditions and co-interventions used.
- EEG recording: electrode numbers and location, eyes opened/closed, sampling rate, filter properties, room characteristics, participant position, duration of recording, timing of recording in respect to intervention.
- PAF calculation: length of epochs, frequency conversion method, bins, and range used, as well as PAF calculation method, and regions of interest.
- Outcomes: pre- and post-intervention PAF means and standard deviations (SDs), mean differences (MDs) and SDs, standardised mean difference (i.e., effect sizes), their variance and standard error (SE) of variance, as well as F-values, t-values, and p-values when means and SDs were not available.

2.7 | Missing data

Corresponding authors were contacted up to three times via email to request missing data. In cases where no reply was received within six weeks of the third contact attempt, data were deemed inaccessible. Data were extracted from figures where possible.

2.8 | Risk of bias and EEG methodological assessment

Risk of bias was assessed using version 6 of the Cochrane Collaboration's tool for assessing risk of bias (Higgins et al., 2011; Sterne et al., 2019). Elements of methodology and reporting were assessed using the best practice recommendations for MEG and EEG (i.e., MEEG) data produced by the Committee on Best Practice in Data Analysis and Sharing (COBIDAS) (Pernet et al., 2018). The COBIDAS MEEG guidelines were adapted to allow MEEG analysis and reporting to be summarised for the PAF outcome (Supplementary Material 2). Two independent reviewers conducted risk of bias and MEEG methodology assessments. Inconsistencies were resolved by a third reviewer where required.

2.9 | Data synthesis

Data were synthesised according to the type of NIBS intervention (i.e., separate groups for tACS, rTMS, tDCS). Where interventions had multiple components or conditions with co-interventions (e.g., tDCS with exercise), only the data from the NIBS intervention component were used (McKenzie et al., 2021). When several post-intervention time points were collected (e.g., 5, 10, 15, and 20 min post-intervention), the most commonly used time point across studies of the same NIBS intervention was used to avoid issues of multiplicity (McKenzie et al., 2021). When two or more time points were used equally across studies, the earliest time point was used.

2.9.1 | Meta-analyses

The effect of NIBS interventions on PAF was assessed using mean differences and 95% confidence intervals (CIs) (Borenstein et al., 2009). To synthesise data, random-effects, pair-wise meta-analyses were conducted in RevMan (version 5.4.). Weight was dependent on sample size and amount of variance in outcome within a study. The results of the meta-analyses are presented as forest plots that indicate either increased or decreased PAF following intervention. The distribution of effect sizes were visually examined for each analysis. As studies with small sample sizes were included, and Cohen's d tends to over-estimate standardised mean difference in such cases (Borenstein et al., 2009), d was converted to Hedges' g (Hedges, 1981). The heterogeneity was considered significant when $p < 0.1$ in a χ^2 test. I^2 was calculated and values greater than 50% denote important variability across studies that is not due to sampling error (Borenstein et al., 2009, 2017).

2.9.2 | Subgroup analyses

Based on entrainment principles (Thut, Schyns, & Gross, 2011; Vogeti et al., 2022), using stimulation frequencies above, below, or at an individual PAF, should increase, decrease, or have no effect on PAF, respectively. Therefore, tACS conditions were grouped into stimulation frequencies above baseline PAF, below baseline PAF, and those without individualised directions for a subgroup analysis. Due to insufficient numbers of included studies, data were not separated by age, sex, or EEG parameters as planned in the protocol (https://osf.io/2yaxz/).

2.9.3 | Sensitivity analysis

Sensitivity analyses were not performed by removing studies with high risk of bias (Deeks et al., 2021) as planned in the protocol (https://osf.io/2yaxz/), because all included studies had low risk of bias.

2.9.4 | Alternative data synthesis

When meta-analysis was not possible for a particular type of NIBS, an alternative synthesis was conducted based on the Synthesis Without Meta-analysis (SWiM) reporting guidelines (Campbell et al., 2020). For each intervention type, a description of the synthesised findings, the level of certainty in the findings, and possible limitations to the synthesis are described (Campbell et al., 2020).

Where possible, pre- and post-intervention means, SDs mean differences, and standardised mean differences (i.e., estimate of effect), as well as variance and direction of effects on PAF, are reported. Within tables, studies are ordered based on possible differences related to PICO elements (i.e., participant, intervention, control, outcome) to informally highlight possible sources of heterogeneity.

2.9.5 | Certainty of evidence

Certainty of evidence, as defined in previous studies (Buscemi et al., 2017; Karjalainen et al., 2001; McLean et al., 2010; Scholten-Peeters et al., 2003), forms the basis of prioritising results for summary and conclusion:

- Strong evidence: consistent findings from two or more cohorts with low risk of bias.
- Moderate evidence: consistent findings from at least one cohort with low risk of bias and one or more cohorts with high risk of bias.

- Limited evidence: findings from only one study with low risk of bias or consistent findings in one or more studies with high risk of bias.
- Conflicting evidence: inconsistent findings irrespective of risk of bias.
- No evidence: no studies found.

3 | RESULTS

3.1 | Search results

The initial search for all types of interventions used to modulate PAF (e.g., exercise, drugs, NIBS) in EMBASE, PsychINFO, PubMed, Scopus, and the Cochrane library in February 2021 provided a total of 6609 references. After adjusting for duplicates, 4827 abstracts were screened, after which 530 full-texts were screened. A total of 86 studies met the inclusion criteria for all varieties of PAF modulators, nine of which were NIBS interventions. The second search with only NIBS key terms (deviations tracked: https://osf.io/2yaxz/) identified 284 additional references of which 213 abstracts were screened after removing duplicates. Fifty full-texts were screened, resulting in two additional NIBS studies that met the inclusion criteria published between February 2021 and April 2023. Therefore, a total of 11 NIBS studies were identified for inclusion in the review (Anderson et al., 2007; Capotosto et al., 2014; Haberbosch et al., 2019; Kleinert et al., 2017; Okamura et al., 2001; Pahor & Jaušovec, 2016; Ronconi et al., 2020; Sato et al., 2021; Stecher et al., 2021; Stecher & Herrmann, 2018; Steinmann et al., 2022). See Figure 1 for study selection summary.

In total, the included studies involved 212 healthy adult participants. Participant age was not reported by one study (Anderson et al., 2007). Three types of NIBS

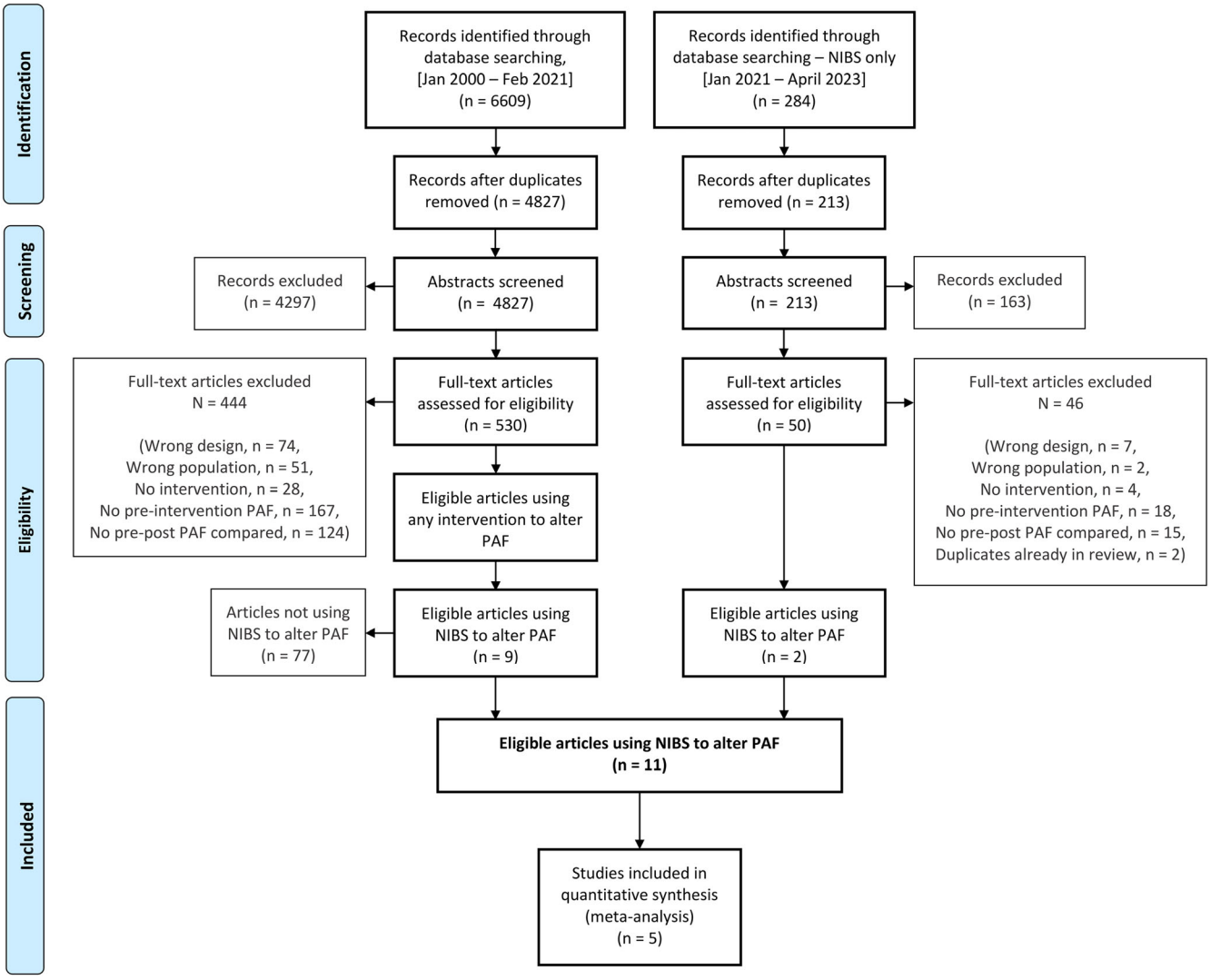

FIGURE 1 Preferred reporting items for systematic reviews and meta-analysis (PRISMA) flow diagram of the screening and inclusion of studies. NIBS = non-invasive brain stimulation; PAF = peak alpha frequency.

interventions were identified: tACS (n = 7 studies) (Haberbosch et al., 2019; Kleinert et al., 2017; Pahor & Jaušovec, 2016; Ronconi et al., 2020; Stecher et al., 2021; Stecher & Herrmann, 2018; Steinmann et al., 2022), rTMS (n = 3 studies) (Anderson et al., 2007; Capotosto et al., 2014; Okamura et al., 2001), and tDCS (n = 1 study) (Sato et al., 2021). The study designs included repeated measures (n = 1), parallel groups (n = 5), and crossover designs (n = 5). Six studies were randomised, controlled, and three studies were non-randomised, controlled. See Table 1 for further details.

3.2 | EEG methodology and quality

Table 2 shows a summary of EEG methodology. The average score for the EEG methodological assessment was 0.50 out of a maximum score of 1.0 (range: 0.35–0.61). The reliability and precision of PAF measurements can be altered by a variety of factors, such as the recording duration, PAF calculation method, and whether data are recorded with eyes opened or closed (Chiang et al., 2011; Chowdhury et al., 2023; Corcoran et al., 2018), these points are discussed below. However, in a comparison of pre-processing methods, where we compared a maximum cleaning pipeline to a no clean pipeline, we showed that earlier pre-processing methods (e.g., artefact rejection, re-referencing, etc.,) do not influence PAF (Chowdhury et al., 2023). Therefore, further comments on the earlier preprocessing steps are not made, besides recognising that there is inconsistent reporting and heterogeneity in the execution of earlier pre-processing steps, which is reflected by the methodological assessment conducted on included studies.

All studies reported using seated resting state EEG data, recorded immediately before and after NIBS interventions, and all reported whether resting state EEG was recorded with eyes open or eyes closed. Specifically, three studies recorded with eyes open (Capotosto et al., 2014; Stecher et al., 2021; Stecher & Herrmann, 2018), five with eyes closed (Anderson et al., 2007; Okamura et al., 2001; Pahor & Jaušovec, 2016; Ronconi et al., 2020; Sato et al., 2021), and three recorded both conditions (Haberbosch et al., 2019; Kleinert et al., 2017; Steinmann et al., 2022). One study did not have *pure* resting states as participants watched a video during resting states recorded inside an MRI scanner (Steinmann et al., 2022).

Seven studies recorded the resting state EEG for two or more minutes (Kleinert et al., 2017; Pahor & Jaušovec, 2016; Ronconi et al., 2020; Sato et al., 2021; Stecher et al., 2021; Stecher & Herrmann, 2018; Steinmann et al., 2022), while the remainder recorded for less than two minutes (range: 2 s–1.5 min) (Anderson et al., 2007; Capotosto et al., 2014; Haberbosch et al., 2019; Okamura et al., 2001). No study reported the number of electrodes excluded or interpolated, how many artefact-free epochs were included, or the length of time included per condition for the PAF calculation, except for Haberbosch et al. (2019) who reported 25 s of artefact-free data.

Most studies reported using fast Fourier transforms (FFT) (Anderson et al., 2007; Haberbosch et al., 2019; Kleinert et al., 2017; Okamura et al., 2001; Ronconi et al., 2020; Stecher et al., 2021), while some were unclear on the spectral analysis method used (Capotosto et al., 2014; Sato et al., 2021; Stecher & Herrmann, 2018) whilst reporting use of hanning windows or referring to methods conducted by Klimesch et al. (1998). One study accounted for the 1/f characteristic of the power spectrum by multiplying the power at each frequency with the respective frequency (Stecher et al., 2021). Regarding, the range used for alpha, five studies used an 8–12 Hz alpha range (Anderson et al., 2007; Haberbosch et al., 2019; Kleinert et al., 2017; Ronconi et al., 2020; Steinmann et al., 2022), three used 7–14 Hz (Capotosto et al., 2014; Pahor & Jaušovec, 2016; Sato et al., 2021), one used 7.2–12.8 Hz (Stecher et al., 2021), and one used 7.5–12 Hz (Stecher & Herrmann, 2018). Most studies used the peak picking method of determining PAF, where PAF is defined as the point at which power is maximal within a specified alpha range, identified visually or with a max function (Anderson et al., 2007; Capotosto et al., 2014; Haberbosch et al., 2019; Kleinert et al., 2017; Ronconi et al., 2020; Stecher et al., 2021; Steinmann et al., 2022). Two studies did not use the peak picking method; Sato et al. (2021) used the centre of gravity (CoG) method and Pahor and Jaušovec (2016) used the channel reactivity based (CRB) method. The CoG method describes PAF as the weighted sum of spectral elements with a specified alpha range, computed by dividing the sum of the products of frequency and power by the sum of power across the frequency band (Brötzner et al., 2014; Jann et al., 2012, 2010; Klimesch, 1999; Klimesch et al., 1993). The CRB method assesses the reactivity of alpha oscillations across multiple channels, relying on this reactivity rather than the presence of spectral peaks (Goljahani et al., 2014, 2012). Various electrodes were used for determining PAF (Table 2), with three studies not reporting which electrodes were used (Anderson et al., 2007; Capotosto et al., 2014; Pahor & Jaušovec, 2016).

3.3 | Risk of bias

One study had 'some concerns' regarding overall risk of bias (Steinmann et al., 2022), while all other studies had

TABLE 1 Characteristics of included studies.

Author and year	Sample size (F/M)	Mean age (SD) unless stated	Study design	NIBS type	Condition	Stim frequency (phase)	Stim intensity	Stim location	Number of blocks	Duration of blocks	Total duration of intervention
Pahor and Jaušovec (2016)	20 (11/9)	20.18 (0.4)	Randomised, counter-balanced, cross-over design	**tACS**	1 active cond	PAF +1Hz	Modus = 1750 μA (peak-to-peak); range = 1000 μA	Left (F3) and right (F4) dorsolateral prefrontal cortex	1	15 min (ramp up/down 15 s)	15 min
Kleinert et al. (2017)	18 (9/9)	25.2 (2.96)	Non-randomised, Orthogonalised, cross-over design	**tACS**	Active cond1: In-phase	5 Hz (0°)	1 mA (peak-to-peak)	F4 and P4 (return at Cz)	1	26 min (ramp up/down 15 s)	26 min
					Active cond2: Anti-phase	5 Hz (180°)	1 mA (peak-to-peak)	F4 and P4 (return at Cz)	1	26 min (ramp up/down 15 s)	26 min
Stecher and Herrmann (2018)	30 (16/14) [Cond1: 15 (8/7); Cond2: 15 (8/7)]	Cond1: 24 (2.4); Cond2: 23.8 (2.8)	Randomised, parallel design	**tACS**	Active cond1: Increasing sequence	Baseline PAF	1 mA	Oz small and Cz large electrode	4	1-, 3-, 5-, then 10-min	18 min
					Active cond2: Decreasing sequence	Baseline PAF	1 mA	Oz small and Cz large electrode	4	10-, 5-, 3-, then 1-min	18 min
Haberbosch et al. (2019)	15 (8/7)	23.9 (2.5)	Non-randomised, parallel design	**tACS**	1 active cond	10 Hz	120% phosphene threshold (mean = 354.15 μA ± 50.6 (peak-to-peak))	Four electrodes above and below eyes	6	30 s (30 s pauses)	6 min
Ronconi et al. (2020)	21 (12/9)	24.5 (range: 20–32)	Non-randomised, counter-balanced, cross-over design	**tACS**	Active cond1: +2 Hz	1) baseline PAF +2Hz	1 mA	P4 stimulated with four return electrodes (C4, Pz, O2, P8)	1	40 min (20-second ramp up)	40 min
					Active cond2: −2 Hz	2) baseline PAF −2Hz	1 mA	P4 stimulated with four return electrodes (C4, Pz, O2, P8)	1	40 min (20-second ramp up)	40 min
Stecher et al. (2021)	Total: 60; Cond1: 18 (8/10); Cond2: 17 (9/8)	Total: 24.4 (3)	Randomised, parallel design	**tACS**	Active cond1: Baseline PAF	Baseline PAF	1 mA (peak-to-peak)	Cz and Oz to target the parieto-occipital cortex	150	8 s (8-second pauses)	40 min
					Active cond2: Closed-loop PAF	Closed-loop PAF	1 mA (peak-to-peak)	Cz and Oz	150	8 s (8-second pauses)	40 min
Steinmann et al. (2022)	22 (13/9) - 18 analysed	24.2	Randomised, cross-over design	**tACS**	1 active cond	Baseline PAF	1 mA (peak-to-peak)	P7 and P8 to target occipital cortex	1	7 min	7 min
	20 (0/20)			**rTMS**	1 active cond	10 Hz		Left prefrontal area	2		5 min 6 s

TABLE 1 (Continued)

Author and year	Sample size (F/M)	Mean age (SD) unless stated	Study design	NIBS type	Condition	Stim frequency (phase)	Stim intensity	Stim location	Number of blocks	Duration of blocks	Total duration of intervention
Okamura et al. (2001)		27 (range: 22–28)	Randomised, parallel design				100% MT of right abductor pollicis brevis muscle			3 s per block (interval 300 s)	
Anderson et al. (2007)	10 (NR)	NR	Randomised, parallel design	**rTMS**	1 active cond	10 Hz	100% MT	Sensors F3 and F4 (× 2 on one side, rest 10–15 min then repeat on other side)	5	5 s (interval 12 s)	1 min 42 s
Capotosto et al. (2014)	15 (6/9)	Range: 21–27	Randomised, repeated measures design	**rTMS**	Active cond1: Right IPS	1 Hz	100% MT	Right IPS	1	1 min	1 min (5 min between each cond)
					Cond2: Left IPS	1 Hz	100% MT	Left IPS	1	1 min	1 min
					Cond3: Right FEF	1 Hz	100% MT	Right FEF	1	1 min	1 min
					Cond4: Left FEF	1 Hz	100% MT	Left FEF	1	1 min	1 min
					Cond5: Right AG	1 Hz	100% MT	Right AG	1	1 min	1 min
					Cond6: Left AG	1 Hz	100% MT	Left AG	1	1 min	1 min
Sato et al. (2021)	10 (4/6)	27 (range: 27–41)	Randomised, cross-over design	**tDCS**	1 active cond (not including exercise)	NR	2 mA (ramp up/down 15 s)	M1 through C3 anode, right supraorbital region	1	20 min	20 min

Abbreviations: AG, angular gyrus; Cond, condition; FEF, frontal eye fields; IPS, intraparietal sulcus; MT, motor threshold; NIBS, non-invasive brain stimulation; NR, not reported; PAF, peak alpha frequency; rTMS, repetitive transcranial magnetic stimulation; SD, standard deviation; Stim, stimulation; tACS, transcranial alternating current stimulation; tDCS, transcranial direct current stimulation.

TABLE 2 Summary of resting state electroencephalography (EEG) methods.

Author and year	Alpha range (Hz)	Regions/ electrodes	Recording interval(s) pre-intervention (duration)	Recording interval(s) post-intervention (duration)	Eyes open/ closed	Recorded duration ≥ or 2 min	Epoch length (s)	Sampling rate (Hz)
Pahor and Jaušovec (2016)	7–14	NR	Immediately before (3 min)	Immediately after (3 min)	Closed	≥ 2 min	11	1000
Kleinert et al. (2017)	8–12	Fz, F8, Pz, P8, Oz	7 min before (2 min open; 2 min closed)	Immediately after (2 min open; 2 min closed)	Open and closed	≥ 2 min	NR	1000
Stecher and Herrmann (2018)	7.5–12	Global (23 electrodes)	Immediately before (3 min)	Immediately after (10 min)	Open	≥ 2 min	1	10,000
Haberbosch et al. (2019)	8–12	Global (32 electrodes)	2.5 s before (30 s open; 30 s closed)	2.5 s after (25 s)	Open and closed	2 min	25	2000
Ronconi et al. (2020)	8–12	Global (8 electrodes)	Immediately before (3 min)	Immediately after (3 min)	Closed	≥ 2 min	1	500
Stecher et al. (2021)	7.2–12.8	Pz	Immediately before (10 min)	Immediately after (10 min)	Open	≥ 2 min	1	250
Steinmann et al. (2022)	8–12	Occipital (O1, Oz, O2, POz)	Before outside scanner (3 min); immediately before inside scanner (7 min)	Immediately after inside scanner (7 min)	Closed outside scanner; open inside scanner	≥ 2 min	10	1000
Okamura et al. (2001)	8–12	F3, F4, C3, C4, P3, P4, T3, T4, T5, T6, Fz, Cz, Pz, Oz	Immediately before (5 min)	Immediately after (5 min [intervals: 0–1 min; 1–2 min; 2–3 min; 3–4 min])	Closed	2 min	Continuous (4-second window)	500
Anderson et al. (2007)	8–12	NR	Immediately before (2 s)	Immediately after (2 s)	Closed	2 min	2	256
Capotosto et al. (2014)	7–14	NR	Immediately before (1.5 min)	Immediately after (2 min [intervals: 0–1 min; 1–2 min])	Open	2 min	2	256
Sato et al. (2021)	7–14	Frontal (Fp1, Fp2, F3, Fz, and F4), central (FC1, FC2, C3, Cz, and C4), parietal (CP1, CP2, P3, P4, and Pz), and occipital (O1, O2, and Oz) ROIs	Immediately before (3 min)	Immediately after (10 min)	Closed	≥ 2 min	NR	2048

Abbreviation: NR, not reported.

a 'low' risk of bias (Figure 2). Two studies had 'some concerns' in the "deviations from the intended interventions" domain, because of a lack of reported information (Haberbosch et al., 2019; Sato et al., 2021). Additionally, two studies had 'some concerns' in the "selection of reported results" domain, because they conducted multiple analyses or outcomes without a pre-registered analysis plan (Stecher et al., 2021; Steinmann et al., 2022).

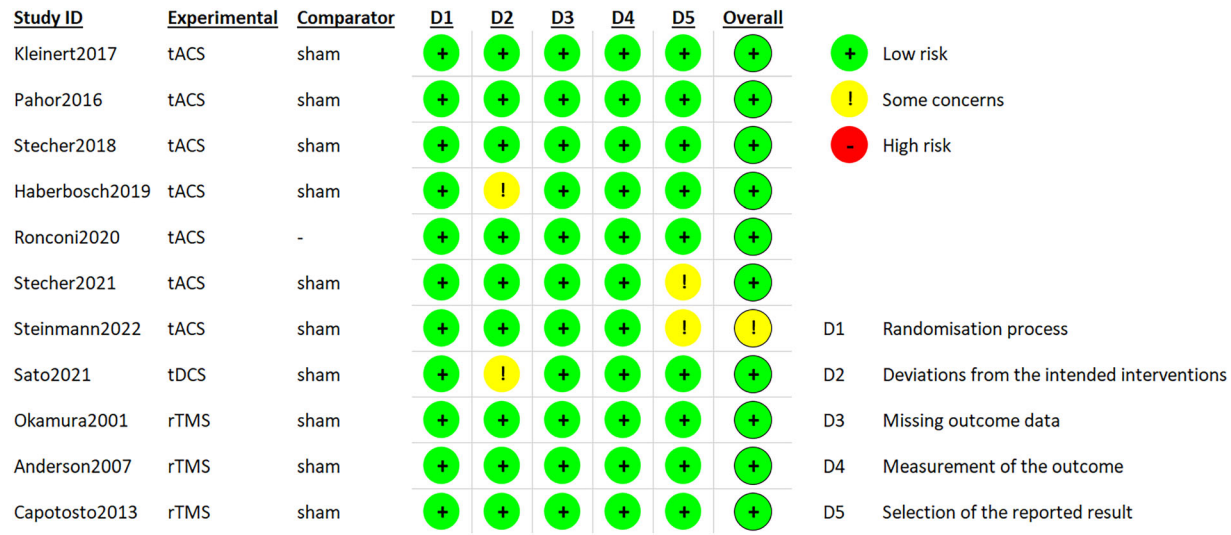

FIGURE 2 Risk of bias results for included studies, using version 6 of the Cochranes Collaboration's tool for assessing risk of bias (Higgins et al., 2011; Sterne et al., 2019).

3.4 | Effects of tACS on PAF

The characteristics of the seven tACS studies are displayed in Table 1. Two authors could not provide pre- and post-tACS PAF means and SDs, so these studies were excluded from the meta-analysis (Kleinert et al., 2017; Steinmann et al., 2022). Pre- and post-tACS PAF means and SDs were collected from eight conditions across the remaining five studies.

3.4.1 | Meta-analysis of tACS effects on PAF

The eight active tACS conditions included in the meta-analysis varied in stimulation parameters, including stimulation location (i.e., central (Pahor & Jaušovec, 2016; Stecher & Herrmann, 2018), parietal (Ronconi et al., 2020), central-parietal (Stecher et al., 2021), and around the eyes (Haberbosch et al., 2019)), duration (i.e., 6 (Haberbosch et al., 2019), 15 (Pahor & Jaušovec, 2016), 18 (Stecher & Herrmann, 2018), and 40 min (Ronconi et al., 2020; Stecher et al., 2021)), and frequency. Stimulation frequencies used included 10 Hz fixed frequency (Haberbosch et al., 2019), above each individual's PAF (i.e., +1 Hz (Pahor & Jaušovec, 2016) and +2 Hz (Ronconi et al., 2020)), below each individual's PAF (i.e., −2 Hz (Ronconi et al., 2020)), fixed at individual PAF (Stecher et al., 2021; Stecher & Herrmann, 2018), or a closed-loop PAF stimulation that calculated a new PAF and adjusted stimulation frequency every 8 s (Stecher et al., 2021) (Table 1). Meta-analysis showed no change in PAF after tACS intervention (5 studies, 8 conditions, 141 participants, MD = −0.12, 95% CI = −0.32 to 0.08, $Z = 1.18$, $p = 0.24$, $X^2(7) = 3.88$, $p = 0.79$ $I^2 = 0\%$; Figure 3).

The lack of general effects of tACS on PAF, could be explained by the variety of stimulation parameters used. Because of the potential for different stimulation frequencies to alter the effect of tACS on PAF, based on entrainment theory (Lakatos et al., 2019; Thut, Schyns, & Gross, 2011; Vogeti et al., 2022), a subgroup analysis was conducted for this stimulation parameter.

3.4.2 | Subgroup meta-analysis based on tACS stimulation frequency

Two tACS conditions applied stimulation above individual PAF (i.e., +1 Hz and +2 Hz) (Pahor & Jaušovec, 2016; Ronconi et al., 2020). Pair-wise comparisons showed no increases in PAF (41 participants, MD = 0.02, 95% CI = −0.37 to 0.40, $Z = 0.09$, $p = 0.93$, $X^2(1) = 1.12$, $p = 0.29$, $I^2 = 11\%$; Figure 3). One condition applied tACS below individual PAF (i.e., −2 Hz) (Ronconi et al., 2020), showing no decreases in PAF (21 participants, MD = −0.23, 95% CI = −0.68 to 0.22, $Z = 0.99$, $p = 0.32$). Five conditions did not individualise tACS (i.e., stimulated at fixed or closed-loop individual PAF (Stecher et al., 2021; Stecher & Herrmann, 2018), or at a fixed 10 Hz (Haberbosch et al., 2019)). No differences in PAF were found after tACS under these conditions (79 participants, MD = −0.16, 95% CI = −0.45 to 0.13, $Z = 1.10$, $p = 0.27$, $X^2(4) = 1.96$, $p = 0.74$, $I^2 = 0\%$).

3.5 | Effects of rTMS on PAF

Characteristics of three rTMS studies are displayed in Table 1, (Anderson et al., 2007; Capotosto et al., 2014;

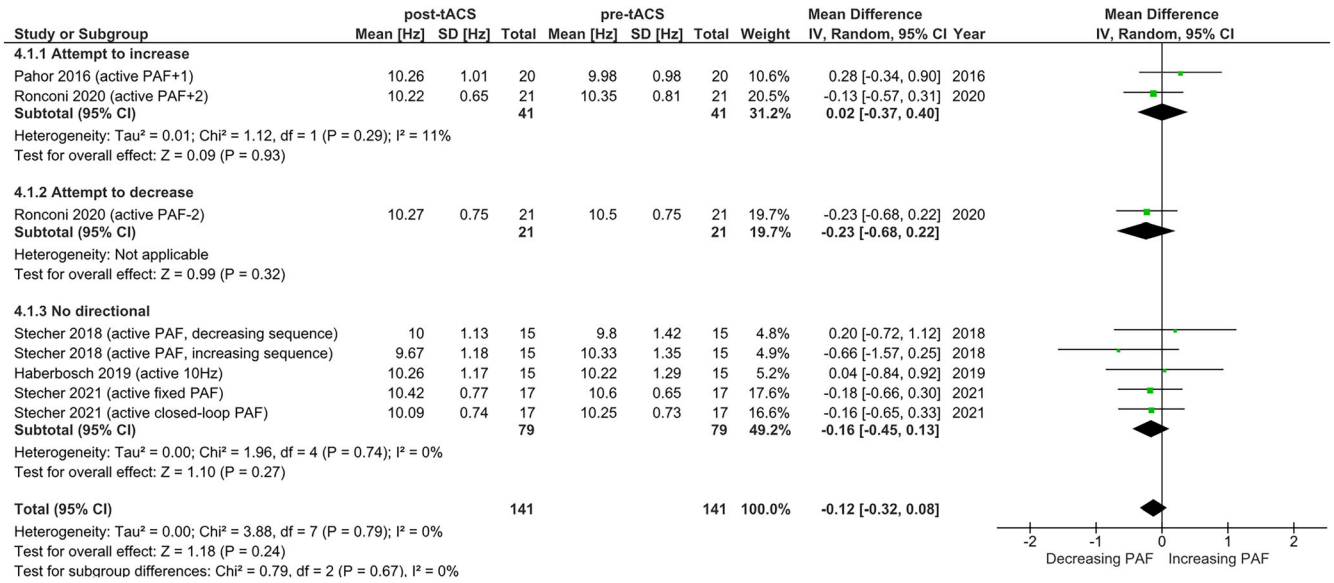

FIGURE 3 Forest plot showing studies that measured peak/individual alpha frequency (PAF/IAF) pre- and post-transcranial alternating current stimulation (tACS) interventions.

Okamura et al., 2001) and are synthesised qualitatively, because of lack of data. Capotosto et al. (2014) applied singular one-minute blocks of 1 Hz rTMS at 100% of motor threshold (MT) to six different brain regions separately (i.e., the right and left for intraparietal sulcus, frontal eye fields, tACS and angular gyrus) in 15 participants. They reported no evidence for PAF modulation at any location (Capotosto et al., 2014). Anderson et al. (2007) applied five blocks of 10 Hz rTMS, lasting 5 s each block, to the dorsal lateral pre-frontal cortex (DLPFC) in 10 participants, finding evidence for an increase in PAF. Okamura et al. (2001) applied two blocks of 10 Hz rTMS, lasting 3 s each block, to the left pre-frontal area in 20 participants, finding evidence for increases in PAF lasting for 1–2 min after rTMS. These PAF increases were found in frontal and central sensors (i.e., F3, F4, C3, T3, T4, Fz, and Cz). In summary, there is moderate evidence from two studies that stimulation at 10 Hz to frontal regions could increase PAF (Anderson et al., 2007; Okamura et al., 2001).

3.6 | Effects of tDCS on PAF

Only one study investigated the effect of tDCS on PAF with 10 participants (Sato et al., 2021) (Table 1). Sato et al. (2021) applied 2 mA anodal tDCS for a singular 20-minute block to the left M1, finding no effect on PAF in any of the four regions of interest (i.e., frontal, central, parietal, occipital).

4 | DISCUSSION

This is the first systematic review to synthesise the evidence for the effect of NIBS interventions on PAF speed. Eleven studies using tACS (seven studies), rTMS (three studies), and tDCS (one study) were included. There was moderate evidence for increased PAF speed from two studies applying rTMS at 10 Hz to frontal regions and no evidence that tACS or tDCS modulated PAF speed. Overall, the evidence is limited, and heterogeneity of stimulation parameters hampers conclusions.

4.1 | tACS does not alter PAF

tACS delivers sinusoidal currents to the brain at a specific frequency and is thought to modify synaptic activity by rhythmically altering neuron membrane potentials and the likelihood of neuronal firing, offering the potential to modulate brain oscillations (Bergmann & Hartwigsen, 2021; Fröhlich & McCormick, 2010; Frohlich & Riddle, 2021; Herrmann et al., 2013;Thut, Schyns, & Gross, 2011; Vogeti et al., 2022). However, there was no evidence of an effect of tACS on PAF in this review (Haberbosch et al., 2019; Kleinert et al., 2017; Pahor & Jaušovec, 2016; Ronconi et al., 2020; Stecher et al., 2021; Stecher & Herrmann, 2018; Steinmann et al., 2022). Definitive conclusions are limited because of the scarcity of studies, small sample sizes, and substantial heterogeneity in stimulation parameters, including

frequency (i.e., at individual fixed or closed-loop PAF, PAF + 2 Hz, PAF + 1 Hz, PAF −2 Hz, fixed 10 Hz, fixed 5 Hz), duration (range: 6–40 min), and location (i.e., frontal, parietal, occipital). Given that parameter configurations are likely to directly influence modulation of oscillations (Polanía et al., 2018; Thut, Veniero, et al., 2011; Vogeti et al., 2022), future research should systematically investigate the effects of these parameters on PAF.

Entrainment describes the frequency and phase alignment between oscillatory systems (Pikovsky et al., 2001). In the context of brain oscillations, entrainment refers to the process by which the frequency and phase of neural oscillations synchronise to an external rhythmic stimulus (Frohlich & Riddle, 2021; Lakatos et al., 2019; Pikovsky et al., 2001; Thut, Schyns, & Gross, 2011). Based on the theory of entrainment, stimulation frequencies faster than an individual's PAF should increase PAF speed, while slower frequencies should decrease it (Lakatos et al., 2019; Thut, Veniero, et al., 2011). Subgroup analysis found no effect on PAF, regardless of the stimulation frequency used. Notably however, the largest subgroup stimulated either at a non-individualised frequency (i.e., 10 Hz) or at individual PAF (e.g., fixed or closed-loop). As entrainment theory would predict no change in PAF under these conditions, the insignificant finding is perhaps unsurprising. One condition in the current review stimulated below individual PAF, to the parietal lobe (Ronconi et al., 2020), while two conditions stimulated above PAF, to either parietal (Ronconi et al., 2020) or frontal lobes (Pahor & Jaušovec, 2016). However, stimulating above or below PAF also showed no change in PAF. A recent study corroborated our lack of findings, reporting no effect of left posterior parietal tACS on PAF (N = 21) across various stimulation frequencies (i.e., PAF, PAF + 2 Hz, PAF −2 Hz, and sham stimulation) in a randomised cross-over design (Kemmerer et al., 2022). This study was excluded from the current review because of inclusion of participants older than 65 years (see Materials and methods).

It is plausible that the lack of overall effect is due to stimulation location, as individualised stimulation frequencies are yet to be tested in central or occipital locations. Alternatively, lack of effects may stem from the application of stimulation frequencies that are too far from an individual's baseline PAF, such as PAF ±2 Hz (Kemmerer et al., 2022; Ronconi et al., 2020). According to the physical principles of synchronisation (Pikovsky et al., 2001), it is easier to entrain internal rhythms with external rhythms that closely match in frequency (Thut, Schyns, & Gross, 2011; Vogeti et al., 2022); with existing evidence that higher stimulation intensities are required to achieve entrainment when the frequency is not closely matched (Ali et al., 2013; Frohlich & Riddle, 2021; Huang et al., 2021). However, a comprehensive investigation into the effects of stimulation frequencies above and below individual PAF on PAF modulation is lacking. Future tACS research should use larger sample sizes and adopt smaller increments of stimulation frequencies around individual baseline PAF, such as PAF ±0.2 Hz or PAF ±0.5 Hz, to provide more detailed understanding of the effects of tACS stimulation frequency on PAF.

4.2 | rTMS at 10 Hz may increase PAF

Two studies used 10 Hz rTMS over pre-frontal regions, finding transient increases in PAF (∼1.5 Hz) in frontal, central, and temporal EEG electrodes lasting for 2 min (Anderson et al., 2007; Okamura et al., 2001), suggesting localised effects near the stimulation site. Conversely, one study that examined 5 Hz rTMS over multiple locations found no evidence for PAF modulation (Capotosto et al., 2014). However, caution is needed when interpreting these results because of small sample sizes and the limited number of studies. As well as replication studies, future research could use longer stimulation durations or multiple sessions in larger samples to assess whether sustained change in PAF can be induced by rTMS. Moreover, as current evidence suggests that rTMS-induced PAF changes might be short-lasting, having only been observed for a maximum of 2 min (Anderson et al., 2007; Okamura et al., 2001), it will be important to measure PAF during stimulation in future research to capture transient PAF modulation. Notably, changes in PAF during stimulation have been observed for both tACS (Minami & Amano, 2017) and rTMS (Di Gregorio et al., 2022). It remains inherently challenging to measure the effects of NIBS on oscillations during stimulation because of electrical artefacts (Wagner et al., 2007), but doing so could be pivotal for understanding the extent to which rTMS influences PAF.

Included rTMS studies employed fixed 5 or 10 Hz frequencies; however, literature on PAF modulation during stimulation suggests more robust effects may be induced by applying individualised rTMS frequencies (i.e., PAF ±1 Hz), as indicated by Di Gregorio et al. (2022). Furthermore, studies on rTMS in depression suggest that the proximity of an individual's PAF to the external driving rhythm (i.e., rTMS frequency) has a quadratic relationship with improvements in depression symptoms (Corlier et al., 2019; Roelofs et al., 2021), such that patients with baseline PAF closer to the stimulation frequency of 10 Hz had greater improvements in depressive symptoms than those with baseline PAF further from 10 Hz. This indicates that the relationship between baseline PAF and

stimulation frequency may impact functional outcomes related to PAF speed, alongside the magnitude and direction of PAF change (Corlier et al., 2019; Roelofs et al., 2021). However, these studies did not assess whether PAF was modulated by the stimulation. Future research should investigate effects of individualised stimulation frequencies on PAF and the relationship between baseline PAF and stimulation frequency of rTMS.

4.3 | tDCS does not alter PAF

Research investigating the effect of tDCS interventions on PAF is scarce. One study (Sato et al., 2021) examined the effect of 2 mA tDCS over the motor cortex (C3) on PAF in 10 healthy adult participants, reporting no effect on PAF. However, the study's small sample size limits definitive conclusions. Further research should explore whether tDCS-induced changes in inhibition-excitation balance correlate with PAF alterations and determine optimal stimulation locations, montages, and experimental set-ups. For example, the authors noted that future investigations should reduce the time between stimulation with tDCS and measurement with EEG, as PAF changes may have ended before the researchers were able to conduct the assessment because of the experimental set-up requiring re-application of the EEG cap (Sato et al., 2021). Additionally, a study in children with autism observed PAF increases around the anodal tDCS site (F3) (Amatachaya et al., 2015), suggesting population-specific and/or location-dependent effects.

Furthermore, though combined interventions were excluded from this systematic review (see Materials and Methods), Sato et al. (2021) found that both active tDCS combined with exercise and sham tDCS combined with exercise, produced significant increases in PAF (~0.7 Hz) in occipital electrodes. However, as the authors did not include a condition of exercise alone, it is difficult to disentangle the effects of tDCS on PAF compared with the effects of exercise. A previous review on the effects of exercise on EEG has suggested that PAF speed increases after exercise (Gramkow et al., 2020), in this case following 12 sessions of 30 min on a cycle ergometer over 4 weeks (Gutmann et al., 2018, 2015). Thus, more studies are needed to elucidate the potential effects of tDCS, alone or in combination, on PAF modulation.

4.4 | Recommendations and future directions

Based on this review, future research should: 1) explore smaller increments of stimulation frequencies for tACS around individuals' PAF, such as PAF ±0.2 Hz, or PAF ±0.5 Hz; 2) explore the relationship between baseline PAF and stimulation frequency for tACS and rTMS; 3) attempt to measure PAF during stimulation; 4) use longer durations or multiple sessions of 10 Hz rTMS; and 5) explore individualised stimulation frequencies for rTMS.

In addition, future research should consider the theoretical assumptions underlying NIBS mechanisms on brain oscillations, specifically, the theory of STDP alongside entrainment (Vogeti et al., 2022). While entrainment refers to synchronisation of endogenous oscillations to an external driving frequency, STDP suggests that stimulation leads to synaptic changes based on the timing of neuronal firing in the targeted region (see Vogeti et al. (2022) for a full review). The choice of stimulation parameters, such as the stimulation intensity or timing and duration of stimulation trains, may have varying effects on PAF depending on which theory or combination of theories are employed (Bergmann & Hartwigsen, 2021; Vogeti et al., 2022). In addition, future research could also consider the brain state at the time of stimulation, as the timing of stimulation relative to oscillatory phase has been shown to influence the effects of NIBS on behavioural outcomes related to oscillations (Mahmoud et al., 2024; Wischnewski et al., 2023). While the mechanism through which NIBS may impact PAF remains uncertain, future research should consider these theories in the selection of stimulation parameters and timing of NIBS delivery.

Lastly, future studies should consider the influence of EEG recording, pre-processing, and PAF calculation methods. In the current review, included studies employed varying locations, durations, and resting state conditions (i.e., eyes closed or eyes open) for EEG measurements. These discrepancies in EEG methodology have the potential to influence PAF values and study outcomes (Chowdhury et al., 2023; Corcoran et al., 2018; Furman et al., 2021; Gil Avila et al., 2023; McLain et al., 2022). For example, recording resting state EEG with eyes closed emphasises the contribution of occipital alpha oscillations, as opposed to when eyes are open (Berger, 1929). In addition, the peak picking method of PAF estimation that was used by most included studies, except two (Pahor & Jaušovec, 2016; Sato et al., 2021), overlooks the possibility of multiple alpha peaks in an individual's frequency spectra (Chiang et al., 2008, 2011). This oversight also disregards the potential for changes in PAF speed through relative increases in the power of faster alpha oscillations compared with slower alpha oscillations (Furman et al., 2021). Future studies should carefully consider the conceptualisation, measurement, and quantification of PAF when evaluating the effect of NIBS interventions on PAF. Moreover, it is imperative for future work to adhere to published reporting

guidelines (Pernet et al., 2018, 2020), consider data sharing (Pernet et al., 2020; Ploner et al., 2017), and adopt standardised (Gil Avila et al., 2023) or no-clean (Chowdhury et al., 2023) pre-processing pipelines to enhance research quality, transparency (Cohen, 2017b), and facilitate comparison of PAF values across studies (McLain et al., 2022).

4.5 | Study limitations and constraints

There are several limitations in this review. First, the included studies had small sample sizes and likely had low statistical power. Second, the generalisability of the results to patient populations cannot be inferred, as studies were restricted to healthy populations. Third, the review only considered articles published since 2000, potentially missing relevant work published prior to this period. Fourth, effects of NIBS on PAF during stimulation were not considered in this review. Lastly, the review did not explore the influence of alpha power, despite the extensive literature on NIBS effects on alpha power (Vogeti et al., 2022). Investigating the interactions between power and alpha peaks after NIBS could provide valuable insights into PAF modulation.

5 | CONCLUSION

This systematic review provides preliminary evidence for transient increases in PAF speed after one session of 10 Hz rTMS. Further investigations are warranted to assess the sustained modulation of PAF by 10 Hz rTMS, using multiple sessions or extended stimulation durations. Although tACS did not influence PAF in this analysis, the mechanism of action makes it theoretically likely to influence PAF speed and further studies are warranted. Exploring variations in stimulation parameters (e.g., frequency, intensity, or duration) within tACS interventions could uncover its capacity to affect PAF. Future studies should delve into optimal protocols and parameter settings for rTMS and tACS, while accounting for individual differences. This research has the potential to not only advance our understanding of PAF modulation through NIBS but also to refine existing therapeutic NIBS interventions for conditions associated with slower PAF, such as depression and chronic pain.

AUTHOR CONTRIBUTIONS

Samantha K. Millard: Conceptualization, data curation, formal analysis, methodology, project administration, visualization, writing—original draft. **Darrah B. Speis:** Data curation, formal analysis, methodology, project administration, writing—review and editing. **Patrick Skippen:** Conceptualization, formal analysis, methodology, writing—review and editing. **Alan K. I. Chiang:** Conceptualization, formal analysis, methodology, supervision, validation, writing—review and editing. **Wei-Ju Chang:** Formal analysis, methodology, writing—review and editing. **Andrew J. Lin:** Formal analysis, writing—review and editing. **Andrew J. Furman:** Writing—review and editing. **Ali Mazaheri:** Writing—review and editing. **David A. Seminowicz:** Conceptualization, methodology, supervision, writing—review and editing. **Siobhan M. Schabrun:** Conceptualization, methodology, supervision, writing—review and editing.

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REFERENCES

Ali, M. M., Sellers, K. K., & Fröhlich, F. (2013). Transcranial alternating current stimulation modulates large-scale cortical network activity by network resonance. *Journal of Neuroscience*, *33*, 11262–11275. https://doi.org/10.1523/JNEUROSCI.5867-12.2013

Amatachaya, A., Jensen, M. P., Patjanasoontorn, N., Auvichayapat, N., Suphakunpinyo, C., Janjarasjitt, S., Ngernyam, N., Aree-uea, B., & Auvichayapat, P. (2015). The short-term effects of transcranial direct current stimulation on electroencephalography in children with autism: A randomized crossover controlled trial. *Behavioural Neurology*, *2015*, 928631. https://doi.org/10.1155/2015/928631

Anderson, E. W., Preston, G. A., & Silva, C. T. (2007). Towards development of a circuit based treatment for impaired memory: A multidisciplinary approach. In *2007 3rd international IEEE/EMBS conference on neural engineering* (pp. 302–305). IEEE. https://doi.org/10.1109/CNE.2007.369671

Berger, H. (1929). Über das elektroenkephalogramm des menschen. *Archiv für Psychiatrie Und Nervenkrankheiten*, *87*, 527–570. https://doi.org/10.1007/BF01797193

Bergmann, T. O., & Hartwigsen, G. (2021). Inferring causality from noninvasive brain stimulation in cognitive neuroscience. *Journal of Cognitive Neuroscience*, *33*, 195–225. https://doi.org/10.1162/jocn_a_01591

Biasiucci, A., Franceschiello, B., & Murray, M. M. (2019). Electroencephalography. *Current Biology*, *29*, R80–R85. https://doi.org/10.1016/j.cub.2018.11.052

Bigler, E. D., Johnson, S. C., Jackson, C., & Blatter, D. D. (1995). Aging, brain size and IQ. *Intelligence*, *21*, 109–119. https://doi.org/10.1016/0160-2896(95)90041-1

Bindman, L. J., Lippold, O., & Redfearn, J. (1962). Long-lasting changes in the level of the electrical activity of the cerebral cortex produced by polarizing currents. *Nature*, *196*, 584–585. https://doi.org/10.1038/196584a0

Borenstein, M., Hedges, L., Higgins, J., & Rothstein, H. R. (2009). *Introduction to meta-analysis*. John Wiley & Sons, Ltd.

Borenstein, M., Higgins, J. P., Hedges, L. V., & Rothstein, H. R. (2017). Basics of meta-analysis: I2 is not an absolute measure of heterogeneity. *Research Synthesis Methods*, *8*, 5–18. https://doi.org/10.1002/jrsm.1230

Braga, M., Barbiani, D., Emadi Andani, M., Villa-Sánchez, B., Tinazzi, M., & Fiorio, M. (2021). The role of expectation and beliefs on the effects of non-invasive brain stimulation. *Brain Sciences*, *11*, 1526. https://doi.org/10.3390/brainsci11111526

Breslau, J., Starr, A., Sicotte, N., Higa, J. B. M. S., & Buchsbaum, M. S. (1989). Topographic EEG changes with normal aging and SDAT. *Electroencephalography and Clinical Neurophysiology*, *72*, 281–289. https://doi.org/10.1016/0013-4694(89)90063-1

Brötzner, C. P., Klimesch, W., Doppelmayr, M., Zauner, A., & Kerschbaum, H. H. (2014). Resting state alpha frequency is associated with menstrual cycle phase, estradiol and use of oral contraceptives. *Brain Research*, *1577*, 36–44. https://doi.org/10.1016/j.brainres.2014.06.034

Buscemi, V., Chang, W.-J., Liston, M. B., McAuley, J. H., & Schabrun, S. (2017). The role of psychosocial stress in the development of chronic musculoskeletal pain disorders: Protocol for a systematic review and meta-analysis. *Systematic Reviews*, *6*, 224. https://doi.org/10.1186/s13643-017-0618-0

Campbell, M., McKenzie, J. E., Sowden, A., Katikireddi, S. V., Brennan, S. E., Ellis, S., Hartmann-Boyce, J., Ryan, R., Shepperd, S., Thomas, J., & Welch, V. (2020). Synthesis without meta-analysis (SWiM) in systematic reviews: Reporting guideline. *Bmj*, *368*, l6890. https://doi.org/10.1136/bmj.l6890

Capotosto, P., Babiloni, C., Romani, G. L., & Corbetta, M. (2014). Resting-state modulation of alpha rhythms by interference with angular gyrus activity. *Journal of Cognitive Neuroscience*, *26*, 107–119. https://doi.org/10.1162/jocn_a_00460

Chiang, A., Rennie, C., Robinson, P., Roberts, J., Rigozzi, M., Whitehouse, R., Hamilton, R., & Gordon, E. (2008). Automated characterization of multiple alpha peaks in multi-site electroencephalograms. *Journal of Neuroscience Methods*, *168*, 396–411. https://doi.org/10.1016/j.jneumeth.2007.11.001

Chiang, A., Rennie, C., Robinson, P., Van Albada, S., & Kerr, C. (2011). Age trends and sex differences of alpha rhythms including split alpha peaks. *Clinical Neurophysiology*, *122*, 1505–1517. https://doi.org/10.1016/j.clinph.2011.01.040

Chowdhury, N. S., Skippen, P., Si, E., Chiang, A. K., Millard, S. K., Furman, A. J., Chen, S., Schabrun, S. M., & Seminowicz, D. A. (2023). The reliability of two prospective cortical biomarkers for pain: EEG peak alpha frequency and TMS corticomotor excitability. *Journal of Neuroscience Methods*, *385*, 109766. https://doi.org/10.1016/j.jneumeth.2022.109766

Cohen, M. X. (2017a). Where does EEG come from and what does it mean? *Trends in Neurosciences*, *40*, 208–218. https://doi.org/10.1016/j.tins.2017.02.004

Cohen, M. X. (2017b). Rigor and replication in time-frequency analyses of cognitive electrophysiology data. *International Journal of Psychophysiology*, *111*, 80–87. https://doi.org/10.1016/j.ijpsycho.2016.02.001

Corcoran, A. W., Alday, P. M., Schlesewsky, M., & Bornkessel-Schlesewsky, I. (2018). Toward a reliable, automated method of individual alpha frequency (IAF) quantification. *Psychophysiology*, *55*, e13064. https://doi.org/10.1111/psyp.13064

Corlier, J., Carpenter, L. L., Wilson, A. C., Tirrell, E., Gobin, A. P., Kavanaugh, B., & Leuchter, A. F. (2019). The relationship between individual alpha peak frequency and clinical outcome

with repetitive transcranial magnetic stimulation (rTMS) treatment of major depressive disorder (MDD). *Brain Stimulation*, *12*, 1572–1578. https://doi.org/10.1016/j.brs.2019.07.018

de Vries, M., Wilder-Smith, O. H. G., Jongsma, M. L. A., van den Broeke, E. N., Arns, M., van Goor, H., & van Rijn, C. M. (2013). Altered resting state EEG in chronic pancreatitis patients: Toward a marker for chronic pain. *Journal of Pain Research*, *6*, 815–824. https://doi.org/10.2147/JPR.S50919

Deeks JJ, Higgins JP, Altman DG, 2021. Chapter 10: Analysing data and undertaking meta-analyses. In: Cochrane handbook for systematic reviews of interventions version 6.2 (updated february 2021). Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ,; Welch VA (editors).

Di Gregorio, F., Trajkovic, J., Roperti, C., Marcantoni, E., Di Luzio, P., Avenanti, A., Thut, G., & Romei, V. (2022). Tuning alpha rhythms to shape conscious visual perception. *Current Biology*, *32*, 988–998. https://doi.org/10.1016/j.cub.2022.01.003

Dickinson, A., DiStefano, C., Senturk, D., & Jeste, S. S. (2018). Peak alpha frequency is a neural marker of cognitive function across the autism spectrum. *European Journal of Neuroscience*, *47*, 643–651. https://doi.org/10.1111/ejn.13645

Fauchon, C., Kim, J. A., el-Sayed, R., Osborne, N. R., Rogachov, A., Cheng, J. C., Hemington, K. S., Bosma, R. L., Dunkley, B. T., Oh, J., Bhatia, A., Inman, R. D., & Davis, K. D. (2022). Exploring sex differences in alpha brain activity as a potential neuromarker associated with neuropathic pain. *Pain*, *163*, 1291–1302. https://doi.org/10.1097/j.pain.0000000000002491

Fröhlich, F., & McCormick, D. A. (2010). Endogenous electric fields may guide neocortical network activity. *Neuron*, *67*, 129–143. https://doi.org/10.1016/j.neuron.2010.06.005

Frohlich, F., & Riddle, J. (2021). Conducting double-blind placebo-controlled clinical trials of transcranial alternating current stimulation (tACS). *Translational Psychiatry*, *11*, 284. https://doi.org/10.1038/s41398-021-01391-x

Furman, A.J., Prokhorenko, M., Keaser, M.L., Zhang, J., Chen, S., Mazaheri, A., Seminowicz, D.A., (2021). Prolonged pain reliably slows peak alpha frequency by reducing fast alpha power. bioRxiv 2021–07. https://doi.org/10.1101/2021.07.22.453260

Gil Avila, C., Bott, F.S., Tiemann, L., Hohn, V.D., May, E.S., Nickel, M.M., Zebhauser, P.T., Gross, J., Ploner, M., (2023). DISCOVER-EEG: An open, fully automated EEG pipeline for biomarker discovery in clinical neuroscience. bioRxiv 2023–01. https://doi.org/10.1101/2023.01.20.524897

Goljahani, A., Bisiacchi, P., & Sparacino, G. (2014). An EEGLAB plugin to analyze individual EEG alpha rhythms using the "channel reactivity-based method.". *Computer Methods and Programs in Biomedicine*, *113*, 853–861. https://doi.org/10.1016/j.cmpb.2013.12.010

Goljahani, A., D'Avanzo, C., Schiff, S., Amodio, P., Bisiacchi, P., & Sparacino, G. (2012). A novel method for the determination of the EEG individual alpha frequency. *NeuroImage*, *60*, 774–786. https://doi.org/10.1016/j.neuroimage.2011.12.001

Gramkow, M. H., Hasselbalch, S. G., Waldemar, G., & Frederiksen, K. S. (2020). Resting state EEG in exercise intervention studies: A systematic review of effects and methods. *Frontiers in Human Neuroscience*, *14*, 155. https://doi.org/10.3389/fnhum.2020.00155

Gutmann, B., Huelsduenker, T., Mierau, J., Strueder, H. K., & Mierau, A. (2018). Exercise-induced changes in EEG alpha power depend on frequency band definition mode. *Neuroscience Letters*, *662*, 271–275. https://doi.org/10.1016/j.neulet.2017.10.033

Gutmann, B., Mierau, A., Hülsdünker, T., Hildebrand, C., Przyklenk, A., Hollmann, W., & Strüder, H. K. (2015). Effects of physical exercise on individual resting state EEG alpha peak frequency. *Neural Plasticity*, *2015*, 717312. https://doi.org/10.1155/2015/717312

Haberbosch, L., Schmidt, S., Jooss, A., Köhn, A., Kozarzewski, L., Rönnefarth, M., Scholz, M., & Brandt, S. A. (2019). Rebound or entrainment? The influence of alternating current stimulation on individual alpha. *Frontiers in Human Neuroscience*, *13*, 43. https://doi.org/10.3389/fnhum.2019.00043

Hedges, L. V. (1981). Distribution theory for glass's estimator of effect size and related estimators. *Journal of Educational Statistics*, *6*, 107–128. https://doi.org/10.3102/10769986006002107

Herrmann, C. S., Rach, S., Neuling, T., & Strüber, D. (2013). Transcranial alternating current stimulation: A review of the underlying mechanisms and modulation of cognitive processes. *Frontiers in Human Neuroscience*, *7*, 279. https://doi.org/10.3389/fnhum.2013.00279

Herrmann, C. S., Strüber, D., Helfrich, R. F., & Engel, A. K. (2016). EEG oscillations: From correlation to causality. *International Journal of Psychophysiology*, *103*, 12–21. https://doi.org/10.1016/j.ijpsycho.2015.02.003

Higgins, J. P., Altman, D. G., Gøtzsche, P. C., Jüni, P., Moher, D., Oxman, A. D., Savović, J., Schulz, K. F., Weeks, L., & Sterne, J. A. (2011). The cochrane collaboration's tool for assessing risk of bias in randomised trials. *BMJ*, *343*, d5928. https://doi.org/10.1136/bmj.d5928

Huang, W. A., Stitt, I. M., Negahbani, E., Passey, D. J., Ahn, S., Davey, M., Dannhauer, M., Doan, T. T., Hoover, A. C., Peterchev, A. V., Radtke-Schuller, S., & Fröhlich, F. (2021). Transcranial alternating current stimulation entrains alpha oscillations by preferential phase synchronization of fast-spiking cortical neurons to stimulation waveform. *Nature Communications*, *12*, 3151. https://doi.org/10.1038/s41467-021-23021-2

Jann, K., Federspiel, A., Giezendanner, S., Andreotti, J., Kottlow, M., Dierks, T., & Koenig, T. (2012). Linking brain connectivity across different time scales with electroencephalogram, functional magnetic resonance imaging, and diffusion tensor imaging. *Brain Connectivity*, *2*, 11–20. https://doi.org/10.1089/brain.2011.0063

Jann, K., Koenig, T., Dierks, T., Boesch, C., & Federspiel, A. (2010). Association of individual resting state EEG alpha frequency and cerebral blood flow. *NeuroImage*, *51*, 365–372. https://doi.org/10.1016/j.neuroimage.2010.02.024

Karjalainen, K., Malmivaara, A., van Tulder, M., Roine, R., Jauhiainen, M., Hurri, H., & Koes, B. (2001). Multidisciplinary biopsychosocial rehabilitation for neck and shoulder pain among working age adults: A systematic review within the framework of the cochrane collaboration back review group. *Spine*, *26*, 174–181. https://doi.org/10.1097/00007632-200101150-00012

Kemmerer, S., Sack, A., de Graaf, T., Ten Oever, S., De Weerd, P., & Schuhmann, T. (2022). Frequency-specific transcranial neuromodulation of alpha power alters visuospatial attention performance. *Brain Research*, *1782*, 147834. https://doi.org/10.1016/j.brainres.2022.147834

Kim, J. A., Bosma, R. L., Hemington, K. S., Rogachov, A., Osborne, N. R., Cheng, J. C., Oh, J., Crawley, A. P., Dunkley, B. T., & Davis, K. D. (2019). Neuropathic pain and pain interference are linked to alpha-band slowing and reduced beta-band magnetoencephalography activity within the dynamic pain connectome in patients with multiple sclerosis. *Pain*, *160*, 187–197. https://doi.org/10.1097/j.pain.0000000000001391

Kleinert, M.-L., Szymanski, C., & Müller, V. (2017). Frequency-unspecific effects of θ-tACS related to a visuospatial working memory task. *Frontiers in Human Neuroscience*, *11*, 367. https://doi.org/10.3389/fnhum.2017.00367

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Research Reviews*, *29*, 169–195. https://doi.org/10.1016/S0165-0173(98)00056-3

Klimesch, W., Doppelmayr, M., Russegger, H., Pachinger, T., & Schwaiger, J. (1998). Induced alpha band power changes in the human EEG and attention. *Neuroscience Letters*, *244*, 73–76. https://doi.org/10.1016/S0304-3940(98)00122-0

Klimesch, W., Schimke, H., & Pfurtscheller, G. (1993). Alpha frequency, cognitive load and memory performance. *Brain Connectivity*, *5*, 241–251. https://doi.org/10.1007/BF01128991

Kondacs, A., & Szabó, M. (1999). Long-term intra-individual variability of the background EEG in normals. *Clinical Neurophysiology*, *110*, 1708–1716. https://doi.org/10.1016/S1388-2457(99)00122-4

Lakatos, P., Gross, J., & Thut, G. (2019). A new unifying account of the roles of neuronal entrainment. *Current Biology*, *29*, R890–R905. https://doi.org/10.1016/j.cub.2019.07.075

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P., Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. *Annals of Internal Medicine*, *151*, W–65. https://doi.org/10.1371/journal.pmed.1000100

Lopes da Silva, F. (2013). EEG and MEG: Relevance to neuroscience. *Neuron*, *80*, 1112–1128. https://doi.org/10.1016/j.neuron.2013.10.017

Lopes da Silva, F. (2023). *EEG: Origin and measurement, in: EEG-fMRI: Physiological basis, technique, and applications* (pp. 23–48). Springer.

Mahmoud, W., Baur, D., Zrenner, B., Brancaccio, A., Belardinelli, P., Ramos-Murguialday, A., Zrenner, C., Ziemann, U., (2024) Brain state-dependent repetitive transcranial magnetic stimulation for motor stroke rehabilitation: A proof of concept randomized controlled trial. medRxiv 2024–03. https://doi.org/10.1101/2024.03.10.24304040

Mansouri, F., Fettes, P., Schulze, L., Giacobbe, P., Zariffa, J., & Downar, J. (2018). A real-time phase-locking system for non-invasive brain stimulation. *Frontiers in Neuroscience*, *12*, 877. https://doi.org/10.3389/fnins.2018.00877

Markram, H., Lübke, J., Frotscher, M., & Sakmann, B. (1997). Regulation of synaptic efficacy by coincidence of postsynaptic APs and EPSPs. *Science*, *275*, 213–215. https://doi.org/10.1126/science.275.5297.213

McKenzie, J., Brennan, S., Ryan, R., Thomson, H., Johnston, RV., Cochrane, 2021. Chapter 9: Summarizing study characteristics and preparing for synthesis. In: Cochrane handbook for systematic reviews of interventions version 6.2 (updated february 2021). Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ,; Welch VA (editors).

McLain, N. J., Yani, M. S., & Kutch, J. J. (2022). Analytic consistency and neural correlates of peak alpha frequency in the study of pain. *Journal of Neuroscience Methods*, *368*, 109460. https://doi.org/10.1016/j.jneumeth.2021.109460

McLean, S. M., May, S., Klaber-Moffett, J., Sharp, D. M., & Gardiner, E. (2010). Risk factors for the onset of non-specific neck pain: A systematic review. *Journal of Epidemiology & Community Health*, *64*, 565–572. https://doi.org/10.1136/jech.2009.090720

Minami, S., & Amano, K. (2017). Illusory jitter perceived at the frequency of alpha oscillations. *Current Biology*, *27*, 2344–2351. https://doi.org/10.1016/j.cub.2017.06.033

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Annals of Internal Medicine*, *151*, 264–269. https://doi.org/10.7326/0003-4819-151-4-200908180-00135

Nunez, P. L., & Srinivasan, R. (2006). *Electric fields of the brain: The neurophysics of EEG*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195050387.001.0001

Okamura, H., Jing, H., & Takigawa, M. (2001). EEG modification induced by repetitive transcranial magnetic stimulation. *Journal of Clinical Neurophysiology*, *18*, 318–325. https://doi.org/10.1097/00004691-200107000-00003

Pahor, A., & Jaušovec, N. (2016). Making brains run faster: Are they becoming smarter? *The Spanish Journal of Psychology*, *19*, E88. https://doi.org/10.1017/sjp.2016.83

Pernet, C., Garrido, M., Gramfort, A., Maurits, N., Michel, C., Pang, E., Salmelin, R., Schoffelen, J.M., Valdes-Sosa, P.A., Puce, A. (2018) Best practices in data analysis and sharing in neuroimaging using MEEG. https://doi.org/10.31219/osf.io/a8dhx

Pernet, C., Garrido, M. I., Gramfort, A., Maurits, N., Michel, C. M., Pang, E., Salmelin, R., Schoffelen, J. M., Valdes-Sosa, P. A., & Puce, A. (2020). Issues and recommendations from the OHBM COBIDAS MEEG committee for reproducible EEG and MEG research. *Nature Neuroscience*, *23*, 1473–1483. https://doi.org/10.1038/s41593-020-00709-0

Pikovsky, A., Rosenblum, M., Kurths, J., & Synchronization, A. (2001). A universal concept in nonlinear sciences. *Self*, *2*, 3. https://doi.org/10.1017/CBO9780511755743

Ploner, M., Sorg, C., & Gross, J. (2017). Brain rhythms of pain. *Trends in Cognitive Sciences*, *21*, 100–110. https://doi.org/10.1016/j.tics.2016.12.001

Polanía, R., Nitsche, M. A., & Ruff, C. C. (2018). Studying and modifying brain function with non-invasive brain stimulation. *Nature Neuroscience*, *21*, 174–187. https://doi.org/10.1038/s41593-017-0054-4

Posthuma, D., Neale, M. C., Boomsma, D. I., & De Geus, E. J. C. (2001). Are smarter brains running faster? Heritability of alpha peak frequency, IQ, and their interrelation. *Behavior Genetics*, *31*, 567–579. https://doi.org/10.1023/A:1013345411774

Purpura, D. P., & McMurtry, J. G. (1965). Intracellular activities and evoked potential changes during polarization of motor cortex. *Journal of Neurophysiology*, *28*, 166–185. https://doi.org/10.1152/jn.1965.28.1.166

Ridding, M. C., & Rothwell, J. C. (2007). Is there a future for therapeutic use of transcranial magnetic stimulation? *Nature Reviews Neuroscience*, *8*, 559–567. https://doi.org/10.1038/nrn2169

Roelofs, C. L., Krepel, N., Corlier, J., Carpenter, L. L., Fitzgerald, P. B., Daskalakis, Z. J., Tendolkar, I., Wilson, A., Downar, J., Bailey, N. W., & Blumberger, D. M. (2021). Individual alpha frequency proximity associated with repetitive transcranial magnetic stimulation outcome: An independent replication study from the ICON-DB consortium. *Clinical Neurophysiology*, *132*, 643–649. https://doi.org/10.1016/j.clinph.2020.10.017

Ronconi, L., Melcher, D., Junghöfer, M., Wolters, C. H., & Busch, N. A. (2020). Testing the effect of tACS over parietal cortex in modulating endogenous alpha rhythm and temporal integration windows in visual perception. *European Journal of Neuroscience.*, *55*, 3438–3450. https://doi.org/10.1111/ejn.15017

Sarnthein, J., Stern, J., Aufenberg, C., Rousson, V., & Jeanmonod, D. (2006). Increased EEG power and slowed dominant frequency in patients with neurogenic pain. *Brain*, *129*, 55–64. https://doi.org/10.1093/brain/awh631

Sato, G., Osumi, M., Nobusako, S., & Morioka, S. (2021). The effects of transcranial direct current stimulation combined with aerobic exercise on pain thresholds and electroencephalography in healthy adults. *Pain Medicine*, *22*, 2057–2067. https://doi.org/10.1093/pm/pnab037

Scholten-Peeters, G. G., Verhagen, A. P., Bekkering, G. E., van der Windt, D. A., Barnsley, L., Oostendorp, R. A., & Hendriks, E. J. (2003). Prognostic factors of whiplash-associated disorders: A systematic review of prospective cohort studies. *Pain*, *104*, 303–322. https://doi.org/10.1016/S0304-3959(03)00050-2

Sejnowski, T. J., & Paulsen, O. (2006). Network oscillations: Emerging computational principles. *Journal of Neuroscience*, *26*, 1673–1676. https://doi.org/10.1523/JNEUROSCI.3737-05d.2006

Stecher, H. I., & Herrmann, C. S. (2018). Absence of alpha-tACS aftereffects in darkness reveals importance of taking derivations of stimulation frequency and individual alpha variability into account. *Frontiers in Psychology*, *9*, 984. https://doi.org/10.3389/fpsyg.2018.00984

Stecher, H. I., Notbohm, A., Kasten, F. H., & Herrmann, C. S. (2021). A comparison of closed loop vs. fixed frequency tACS on modulating brain oscillations and visual detection. *Frontiers in Human Neuroscience*, *15*, 661432. https://doi.org/10.3389/fnhum.2021.661432

Steinmann, I., Williams, K. A., Wilke, M., & Antal, A. (2022). Detection of transcranial alternating current stimulation aftereffects is improved by considering the individual electric field strength and self-rated sleepiness. *Frontiers in Neuroscience*, *16*, 870758. https://doi.org/10.3389/fnins.2022.870758

Sterne, J. A., Savović, J., Page, M. J., Elbers, R. G., Blencowe, N. S., Boutron, I., Cates, C. J., Cheng, H.-Y., Corbett, M. S., Eldridge, S. M., & Emberson, J. R. (2019). RoB 2: A revised tool for assessing risk of bias in randomised trials. *Bmj*, *366*, l4898. https://doi.org/10.1136/bmj.l4898

Tement, S., Pahor, A., & Jaušovec, N. (2016). EEG alpha frequency correlates of burnout and depression: The role of gender. *Biological Psychology*, *114*, 1–12. https://doi.org/10.1016/j.biopsycho.2015.11.005

Thut, G., Schyns, P. G., & Gross, J. (2011). Entrainment of perceptually relevant brain oscillations by non-invasive rhythmic stimulation of the human brain. *Frontiers in Psychology*, *2*, 170. https://doi.org/10.3389/fpsyg.2011.00170

Thut, G., Veniero, D., Romei, V., Miniussi, C., Schyns, P., & Gross, J. (2011). Rhythmic TMS causes local entrainment of natural oscillatory signatures. *Current Biology*, *21*, 1176–1185. https://doi.org/10.1016/j.cub.2011.05.049

Van Diepen, R. M., Foxe, J. J., & Mazaheri, A. (2019). The functional role of alpha-band activity in attentional processing: The current zeitgeist and future outlook. *Current Opinion in Psychology*, *29*, 229–238. https://doi.org/10.1016/j.copsyc.2019.03.015

Vogeti, S., Boetzel, C., & Herrmann, C. S. (2022). Entrainment and spike-timing dependent plasticity–a review of proposed mechanisms of transcranial alternating current stimulation. *Frontiers in Systems Neuroscience*, *16*, 827353. https://doi.org/10.3389/fnsys.2022.827353

Vosskuhl, J., Strüber, D., & Herrmann, C. S. (2018). Non-invasive brain stimulation: A paradigm shift in understanding brain oscillations. *Frontiers in Human Neuroscience*, *12*, 211. https://doi.org/10.3389/fnhum.2018.00211

Wagner, T., Valero-Cabre, A., & Pascual-Leone, A. (2007). Noninvasive human brain stimulation. *Annual Review of Biomedical Engineering*, *9*, 527–565. https://doi.org/10.1146/annurev.bioeng.9.061206.133100

Wahbeh, H., & Oken, B. S. (2013). Peak high-frequency HRV and peak alpha frequency higher in PTSD. *Applied Psychophysiology and Biofeedback*, *38*, 57–69. https://doi.org/10.1007/s10484-012-9208-z

Wischnewski, M., Alekseichuk, I., & Opitz, A. (2023). Neurocognitive, physiological, and biophysical effects of transcranial alternating current stimulation. *Trends in Cognitive Sciences*, *27*, 189–205. https://doi.org/10.1016/j.tics.2022.11.013

Zaehle, T., Rach, S., & Herrmann, C. S. (2010). Transcranial alternating current stimulation enhances individual alpha activity in human EEG. *PLoS ONE*, *5*, e13766. https://doi.org/10.1371/journal.pone.0013766

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