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Registered Report

Spatial attention is not affected by alpha or beta transcranial alternating current stimulation: A registered report

Jonathan Silas [a,**,1], Alexander Jones [a,*,1], Kielan Yarrow [b] and Wayne Anderson [a]

[a] Middlesex University London, United Kingdom
[b] City, University of London, United Kingdom

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ABSTRACT

Using Electroencephalography (EEG) an event-related change in alpha activity has been observed over primary sensory cortices during the allocation of spatial attention. This is most prominent during top-down, or endogenous, attention, and nearly absent in bottom-up, or exogenous orienting. These changes are highly lateralised, such that an increase in alpha power is seen ipsilateral to the attended region of space and a decrease is seen contralaterally. Whether these changes in alpha oscillatory activity are causally related to attentional resources, or to perceptual processes, or are simply epiphenomenal, is unknown. If alpha oscillations are indicative of a causal mechanism whereby attention is allocated to a region of space, it remains an open question as to whether this is driven by ipsilateral increases or contralateral decreases in alpha power. This preregistered report set out to test these questions. To do so, we used transcranial Alternating Current Stimulation (tACS) to modulate alpha activity in the somatosensory cortex whilst measuring performance on established tactile attention paradigms. All participants completed an endogenous and exogenous tactile attention task in three stimulation conditions; alpha, sham and beta. Sham and beta stimulation operated as controls so that any observed effects could be attributed to alpha stimulation specifically. We replicated previous behavioural findings in all stimulation conditions showing a facilitation of cued trials in the endogenous task, and inhibition of return in the exogenous task. However, these were not affected by stimulation manipulations. Using Bayes-factor analysis we show strong support for the null hypotheses – that the manipulation of Alpha by tACS does not cause changes in tactile spatial attention. This well-powered study, conducted over three separate days, is an important contribution to the current debate regarding the efficiency of brain stimulation.

*Corresponding author. Department of Psychology, School of Science & Technology, Middlesex University, London NW4 4BT, United Kingdom.
**Corresponding author. Department of Psychology, School of Science & Technology, Middlesex University, London NW4 4BT, United Kingdom.
E-mail addresses: j.e.silas@mdx.ac.uk (J. Silas), a.j.jones@mdx.ac.uk (A. Jones).
[1] Contributed equally to this work and share first authorship.

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1. Introduction

Spatial attention involves orienting to a location which then improves detection and facilitates behavioural responses to stimuli at attended locations (Carrasco, 2014). This has been demonstrated within vision, audition, touch and across the senses using both behavioural and a range of neuroscientific techniques (for reviews see, Spence, 2010; Posner, 2016). Using electroencephalography (EEG), alpha activity (8–14 Hz) was first discovered by Hans Berger in the 1920s (Berger, 1929). This activity was, up until recently, thought to reflect "cortical idling" – a state of wakefulness without engaging in any particular task (Berger, 1929; Lopes; Da Silva, Van Lierop, Schrijer, & Van Leeuwen, 1973; Pfurtscheller, Stancak, & Neuper, 1996). However, there is now strong evidence to suggest that alpha activity has a functional role in cognition and attention in particular (Calderone, Lakatos, Butler, & Castellanos, 2014; Ward, 2003). Shifting attention to a location in space has been shown to modulate alpha power. Specifically, voluntarily shifting covert attention to one side of visual space (e.g., left), leads to a decrease of alpha activity over the contralateral hemisphere (e.g., right) and increases of alpha power over the ipsilateral (e.g., left) hemisphere (Jensen & Mazaheri, 2010; Kelly, Gomez-Ramirez, & Foxe, 2009; Rihs, Michel, & Thut, 2007; Thut, Nietzel, Brandt, & Pascual-Leone, 2006; Worden, Foxe, Wang, & Simpson, 2000). These alpha oscillatory changes have been proposed to reflect a neural mechanism of top-down attention which modulates the gain of sensory input (Ikkai, Dandekar, & Curtis, 2016). In line with this idea, a decrease in alpha power is correlated with enhanced target detection (Gould, Rushworth, & Nobre, 2011; Händel, Haarmeier, & Jensen, 2011; Kelly et al., 2009; Thut et al., 2006). Changes in alpha oscillations have not only been linked to visual attention but are also found when attention is deployed to an upcoming tactile event (Bauer, Kennett, & Driver, 2012; Haegens, Luther, & Jensen, 2012; Jones et al., 2010; Schubert et al., 2015; van Ede, de Lange, Jensen, & Maris, 2011).

Although a number of studies have examined the role of alpha power in the voluntarily shifting of attention (endogenous orienting; Ikkai et al., 2016, Foxe & Snyder, 2011; Jensen & Mazaheri, 2010) few have explored its role in stimulus driven attention (exogenous orienting). Endogenous and exogenous cueing of attention have shown to have largely independent effects on behaviour (Berger, Henik, & Rafal, 2005; Chica, Lupiánez, & Bartolomeo, 2006; Lupiáñez et al., 2004). Although not wholly separate, endogenous predictive cues typically facilitate target detection and non-predictive exogenous cues slow target detection when cue and target appear at the same location (inhibition of return effect) (see Chica, Martín-Arévalo, Botta, & Lupiánez, 2014 for a review of the cue-target paradigm). Neurally, endogenous attention is mediated via the parietal and superior frontal cortex, whereas exogenous attention via a temporo-parietal and inferior frontal cortex (see, Corbetta & Shulman, 2002; Macaluso, 2010 for reviews). Some recent research does suggest that the two attentional systems are more likely to interact when attention is oriented across sensory modalities ((Santangelo, Belardinelli, Spence, & Macaluso, 2009).

More carefully exploring the role of alpha oscillations during exogenous and endogenous orienting, Haegens, Händel, and Jensen (2011) presented participants with a visual cue that directed attention to either the left or right hand where a tactile target was presented. Using a lateralisation index of alpha oscillatory activity they found somatosensory alpha correlated with behavioural performance; accuracy and response times (RTs) improved with the degree of alpha lateralisation. Moreover, somatosensory alpha oscillations were related to how predictable the cue was. The strongest lateralisation was found when the cue was 100% predictive of the target, reduced when 75% predictive and nearly absent when the cue was not predictive (50%). Effectively, when attention was cued endogenously this was associated with greater alpha lateralisation compared to when attention was cued exogenously. The effect was present over somatosensory areas, suggesting modality specific somatosensory alpha oscillation, but which behaves functionally similar to the posterior alpha rhythm shown in the visual modality. Converging evidence for sensory specific oscillations was presented by Bauer et al. (2012) who showed that attending to either touch or vision supressed alpha power in the associated cortical area.

Understanding how alpha oscillations and attention are linked has largely been tackled by measuring EEG/MEG and correlated with behavioural performance in an attentional paradigm. Here we propose a novel approach to studying the alpha–attention relationship by introducing transcranial Alternating Current Stimulation (tACS).

tACS is a relatively new method of modulating cortical activation and has recently been employed to explore the role of on-going neural oscillations in cognition. By applying electrodes to the surface of the scalp and administering a low alternating current, underlying cortical excitation can be manipulated either interfering with, or facilitating, behaviour (Antal & Paulus, 2013). Recent evidence has demonstrated that tACS can modulate intrinsic frequencies in underlying cortical structures (Helfrich et al., 2014). Specifically, both the frequency and the phase of the applied current are matched by the neural rhythm generated in the cortex. Helfrich et al. (2014) applied tACS at 10 Hz over the parieto-occipital cortex while concurrently measuring electroencephalography (EEG). The authors report an increase in power and phase-locking to the alpha 10 Hz rhythm applied by tACS and find no such changes in other intrinsic cortical rhythms (delta & theta band oscillations).

Some research has sought to modulate the central alpha and beta rhythms found over the motor and somatosensory cortices to explore the role of movement and tactile perception respectively. Wach et al. (2013) showed that 10 Hz stimulation over the motor cortex increases movement variability, in particular when tasks require an internal pacing. Krause, Meier, Dinkelbach, and Pollok (2016), showed that inducing beta, but not alpha tACS can facilitate the retrieval of a motor sequence from memory. Although previous studies have used EEG to explore the role of cortical rhythms in tactile perception, little research has used tACS to explore the somatosensory system. Non-invasive brain stimulation techniques allow for experimental designs to infer the causal role of a given brain process for a given cognitive function. In the case of

tACS, directly manipulating an underlying cortical rhythm allows for inferences to be drawn about the role of such rhythms in cognition and behaviour. In a particularly relevant study Gundlach, Müller, Nierhaus, Villringer, and Sehm (2016) modulated the alpha rhythm of participants by applying tACS to the somatosensory cortex. The exact frequency of the tACS was 'individualised' in a pre-experiment such that a peak alpha frequency for each participant was first identified. This was achieved by measuring EEG during the presentation of easily detectable (supra-threshold) somatosensory stimuli to the right index finger, leading to an event-related desynchronization over the somatosensory cortex. The individual frequency for a given participant was defined as the frequency with the lowest, relative to baseline, power averaged across a given time period (200–600 msec post tactile stimuli presentation) within the alpha range (8–14 Hz). In the main experiment Gundlach et al. (2016) then applied tACS (at the participants' individual frequency, as defined in the pre-experiment) while presenting somatosensory stimuli to the right index finger at near detection threshold intensities. Participants responded to targets by pressing a button with their left hand. Importantly, and different to the present study, all stimuli were presented to only one finger, meaning any effects of spatial attention could not be explored. Gundlach et al. (2016) found that the phase of the ongoing alpha rhythm applied to the somatosensory cortex via tACS significantly impacts the perception and detection of tactile stimuli. Whilst novel and important, the research has yet to investigate the role of alpha rhythms in spatial attention and tactile perception. In the current experiment, we outline two well established tasks that tap into exogenously and endogenously driven spatial attention to tactile information. By getting participants to shift their attentional focus to different locations on their body, and using tACS to interfere with typical oscillatory functioning, we are able to examine the causal role of alpha in tactile spatial attention.

More recently, two papers have used tACS to modulate ongoing alpha rhythms and measured an effect on visual attention (Hopfinger, Parsons, & Fröhlich, 2017; van Schouwenburg, Zanto, & Gazzaley, 2017). Both papers use tACS to modulate activity in the right hemisphere during a visual attention paradigm with differing results. Hopfinger et al. (2017) presented participants with peripheral targets, and in the exogenous task the target was preceded by a non-informative peripheral cue on every trial. The endogenous task used a blocked design where the informative cue (an arrow) indicated to which side to orient attention for the entire block of 20 trials. Hopfinger et al. (2017) observe facilitation of RTs to cued targets in both tasks. However, they find that alpha stimulation does not modulate the RT effect, or accuracy, in either task.[2] However, gamma tACS decreased RTs when participants were identifying a target preceded by a cue in the opposite visual field (invalid trials) compared to RTs to the same target during sham stimulation. The authors suggest that this offers support that the right parietal lobe, oscillating at approximately 40 Hz, is involved in disengaging endogenous attention. Using a different tACS stimulation montage, van Schouwenburg et al. (2017) test fronto-parietal alpha frequency coherence. They report that a right visual field bias, observed in the sham stimulation condition, was eliminated during alpha fronto-parietal stimulation. These findings provide little information about the mechanisms involved in selective attention but suggest alpha coherence may be involved in sustained global attentional processes. We suggest that the same is true of the Hopfinger et al. (2017) paper. Given that endogenous cuing was provided at the start of each block, rather than on a trial by trial basis, it is more likely that the effects observed in the endogenous attention task are due to sustained global attentional mechanisms and not event-related selective attentional processes. Furthermore, both papers (Hopfinger et al., 2017; van Schouwenburg et al., 2017), aim to modulate the oscillatory mechanisms, using tACS, in the parietal lobe. Recent research has indeed shown that activation in the right parietal lobule is negatively correlated with alpha amplitude measured on the scalp (Liu, Bengson, Huang, Mangun, & Ding, 2014). The same research also shows that activity in primary sensory cortices is also related to alpha modulations (Liu et al., 2014).

Critically, the tACS studies that have explored the orienting of attention in space have focused on the manipulation of global attentional processes that are likely mediated by brain mechanisms not specific to the modality under investigation. Indeed, gamma oscillations and EEG coherence, as explored by Hopfinger et al. (2017) and van Schouwenburg et al. (2017) respectively, have been implicated in such global attentional processes. However, top-down attentional modulation of alpha oscillations has been shown to be modality specific originating from distinct auditory (e.g., Mazaheri et al., 2014) or tactile sensory areas (Bauer et al., 2012; Haegens et al., 2011; Jones et al., 2010; van Ede et al., 2011). It therefore remains an open question as to whether alpha modulations in primary sensory areas drive tactile spatial attention allocation, and whether this is a mechanism for enhancement of task-relevant information or a suppression of task-irrelevant information.

We outline a research protocol that aims to answer these questions within the tactile sensory modality. Importantly, there are clear contralateral alpha decreases, in cue-target intervals, for tactile selective attention paradigms, over the primary somatosensory cortex (Haegens et al., 2011). The fact that alpha attentional effects are strongly lateralised in touch provides a better opportunity to explore the hemispheric alpha desynchronization and synchronisation effects and their role in attention, compared to vision and audition. Moreover, the somatosensory cortex is situated closer to the scalp surface as compared to primary visual areas, making it better suited to investigate the effects of brain stimulation. By uni-hemispherically interfering with individualised alpha frequencies, during both an endogenous and exogenous cue-target attentional paradigm in the tactile domain, we aim to assess the functional role of alpha oscillatory activity in primary somatosensory cortices. If such activity is causally

[2] Hopfinger et al. (2017) do comment on an effect of alpha stimulation in their reporting of the results. However, the critical interaction effect found is at $F = 3.23$, $p = .086$. Further, subsequent uncorrected post-hoc t tests showing that invalid trials in the exogenous condition are slower in alpha compared to sham stimulation conditions are at $t = 1.87$, $p = .074$. Although they proceed with the interpretation of these findings with caution we consider the effect too small to confirm a positive effect.

related to the selective allocation of attention, alpha stimulation, compared to sham or control-frequency stimulation, should interfere with RTs. Second, because we are modulating uni-hemispherically, we are able to dissociate the attentional processes involved in inhibiting irrelevant information from the attentional processes involved in enhancing relevant information.

Given the complexity of our design we have outlined and graphically represented our hypotheses in the 'hypotheses section' below. These are enumerated and correspond to the appropriate analysis technique outlined in the 'Behavioural data analysis' section. Here, we outline our rationale for each prediction. We expect to replicate RT effects shown by ourselves (Jones & Forster, 2012, 2013, 2014) and others (Spence & Gallace, 2007) in the sham and beta conditions (see hypothesis 3). Specifically, we are basing behavioural RT predictions on Jones and Forster (2014) which explored the effects of both endogenous and exogenous tactile attention in a target detection task using a within-subjects design. In both tasks supra-threshold (easily detectable) tactile stimuli were delivered to the left and right index fingers. Jones and Forster (2014) used a unilateral tactile cue that was followed by a tactile target to the same or opposite hand, separated by an 800 msec cue-target interval. In the endogenous task, the cue was informative (80%) of which hand the target was likely to appear. In the exogenous task, the cue was non-informative (50%) to the target location. Participants responded vocally, using a voicekey, to all targets which were supra-threshold tactile stimuli. Jones and Forster (2014) showed a facilitation effect in the endogenous task with faster RTs for attended compared to unattended targets. Inhibition of return (IOR), with slower responses for cued (cue and target to the same hand) compared to uncued targets (opposite hand), was observed in the exogenous task. We predict similar facilitation and IOR effects in the present study (see outcome-neutral section below). Importantly, however, as alpha tACS stimulation is expected to interfere with endogenous attention only, a facilitation effect should be eliminated in the alpha stimulation condition but should remain in beta and sham conditions. Exogenous attentional processes are not expected to be affected by stimulation at all (see hypothesis 4). The reason for this is that previous research has shown lateralised alpha power, in the cue-target interval, is greater when the cue is predictive of the target, and nearly absent when it is not (Haegens et al., 2011; Trenner et al., 2008). That is to say that when detection of a target is facilitated by an informative endogenous cueing of attention, lateralised alpha power is greatest. Given that we are stimulating uni-hemispherically we expect to interfere with lateralised alpha power that is directly and specifically related to endogenous attentional processes in the tactile domain (Haegens et al., 2011).

Based on comparable endogenous attention research in touch (Haegens et al., 2011) we expect a somatosensory alpha desynchronization contralateral to the attended side and an alpha synchronisation ipsilateral to the attended side, in the cue-target interval. Specifically, when a tactile cue provides predictive information about the location of the target (i.e., an endogenous task) a decrease in alpha power is seen contralateral to the attended location and an increase in power is observed ipsilaterally. However, when a tactile cue provides no information about target location (i.e., an exogenous task), the contralateral decrease and ipsilateral increase in alpha power is weaker or absent. These data suggest lateralised alpha power over the somatosensory cortex reflects a top-down controlled attentional mechanism. However, the causal role of such changes in ongoing rhythms is still unconfirmed. Rhythmic changes measured using EEG could reflect downstream modulation by higher order attentional mechanisms (e.g., Zhang & Ding, 2010) or simply be epiphenomenal. If, as suspected, rhythmic alpha modulations are causally related to somatosensory endogenous attentional orientation, then alpha-tACS stimulation should selectively interfere with target detection for endogenous but not exogenous tasks. Whether it is a contralateral decrease or ipsilateral increase in alpha power that drives attentional allocation of resources is not established (Klimesch, 2012). Uni-hemispheric alpha-stimulation allows for the independent assessment of contra- and ipsilateral tACS interference. We predict a behavioural facilitation of responses, to cued compared to uncued targets, to be eliminated during ipsilateral stimulation only in the endogenous task (see hypothesis 8). Lateralisation, in this context refers to the congruency between stimulated hemisphere and the attended side.

The experimental programme of research that we outline below consists of a pre-experiment and a main experiment run over three days. Participants, after pre-screening, are allocated to a stimulation hemisphere condition that dictates which hemisphere (left or right) will be stimulated during the stimulation protocol (counterbalanced across participants). In the pre-experiment, we propose to use EEG to identify a peak alpha frequency for each participant. This is achieved by measuring EEG while suprathreshold tactile stimuli are delivered to the hand contralateral to the to-be stimulated hemisphere. A functional decrease in alpha power will be calculated, at a central electrode contralateral to the hand that receives the tactile stimuli (C3 or C4), and the frequency where the decrease in alpha power is greatest will be defined as the individual's peak alpha frequency (as in, Gundlach et al., 2016). The main experiment will be run over three different days (at least 12 h apart) under three different tACS conditions, the order of which will be randomly varied across participants. The stimulation conditions are sham (stimulation for 20 sec only), beta (tACS at 25 Hz) or individualised alpha (tACS at frequency defined by pre-experiment). During the stimulation participants will undergo two tasks: exogenous and endogenous orienting. In both tasks participants will respond (vocally) to a supra-threshold lateralised tactile targets to the index fingers. In the exogenous task, the target will be preceded by a non-predictive cue to the same or opposite hand. In the endogenous task, bilateral tactile cues will provide information about the likely location (left or right) of the upcoming tactile target.

1.1. *Outcome-neutral effects*

As well as effects testing our novel hypotheses, we are also expecting to replicate previous results. These predictions serve as outcome-neutral effects that should serve as a 'check' that the experimental manipulations are effective. First, as outlined above, responses in the exogenous task should be

faster for uncued targets compared to cued targets (IOR) and vice versa for the endogenous task (facilitation effect). These are well-established effects (Jones & Forster, 2012, 2013, 2014; Lloyd, Bolanowski, Howard, & McGlone, 1999; Spence & Gallace, 2007) and would confirm the cueing manipulation worked and participants followed instructions (see hypotheses 3, 6 and 7). Along similar lines, research into spatial attentional has shown that exogenous cueing results in faster RTs compared to endogenous cueing (Berger et al., 2005) and we expect to reproduce this (see hypothesis 2).

An outcome-neutral effect is also sought to check that tACS has had an effect on the brain and subsequent RTs. However, studies that we cite as key contributors to our rationale (Gundlach et al., 2016; Hopfinger et al., 2017; van Schouwenburg et al., 2017) find no main effect of brain stimulation, compared to control stimulation, on RTs. Furthermore, the effect of tACS on brain and behaviour is still very much under debate in the literature with recent reports showing very little current actually penetrates the scalp and cerebrospinal fluid (Vöröslakos et al., 2018). Some research has shown that both beta and alpha stimulation, using tACS, can speed RTs in a motor task (Pollock, Boysen & Krause, 2015). However, other research has shown that alpha and beta tACS have differential effects on RTs; alpha leading to a speeding of RTs and beta to a slowing (Cappon, D'Ostilio, Garrauz, Rothwell & Bisiacchi, 2016). One possible check that tACS is having an effect on behaviour might be to expect a change of RTs for beta and alpha stimulation conditions (see hypotheses 1 and 5). Although, not meeting this prediction would not necessarily invalidate our critical interaction hypotheses (hypotheses 4 and 8) it would cause some caution in interpretation of the results as no overall effect of tACS would appear to be present in its effect on behaviour.

Given that tACS at alpha frequencies has been shown to have a phase dependant effect on detection of near-threshold stimuli (Gundlach et al., 2016), there is some concern that a change in RTs as a result of alpha tACS may be due to perceptual and not attentional processes. Although this is unlikely, given our use of supra-threshold stimuli and a random inter-trial-interval resulting in random phase, we propose a manipulation check. Specifically, the elimination of RT differences between cued and uncued conditions should be present in the endogenous task only. If this predicted effect is found to be reversed, such that RT differences are eliminated in the alpha tACS condition for exogenous but not endogenous tasks, it is possible that perceptual processes, rather than attentional ones, were interfered with by tACS. This is due to the fact that any effect on perceptual tactile processes has been shown to be contralateral (Gundlach et al., 2016). In the endogenous task, a tactile cue ipsilateral to the stimulation site is always available. Therefore, if perceptual processes are affected and not attentional processes, there should be no effect on RTs in the endogenous task, only during the exogenous task. Furthermore, to confirm the effect of tACS on perceptual processes during the exogenous task, only RTs where the cue and target are contralateral to the stimulation site should be affected. This possible explanation for the findings will be discussed if RTs are modified by tACS for the exogenous tasks.

2. Hypotheses

Our hypotheses below are enumerated and correspond to the enumeration for the statistical analyses of these hypotheses outlined in the 'Behavioural data analysis' section. We have divided the hypotheses into effects we expect to be modulated by task (exogenous compared to endogenous), independent of cue-stimulation lateralisation, and those we expect to be modulated by cue-stimulation lateralisation (contralateral compared to ipsilateral) independent of task. We also provide graphical representation of our hypotheses.

Task specific effects (see Fig. 1).

1. Main effect of tACS – RTs are expected to differ for alpha and beta stimulation conditions compared to sham stimulation (two-tailed).
2. Main effect of task – RTs in the exogenous task are expected to be faster than RTs in the endogenous task.
3. Interaction between task and cue – In the endogenous task, responses to cued targets are expected to be faster than responses to uncued targets (commonly referred to as a facilitation effect). However, in the exogenous task, RTs are expected to be faster for uncued targets compared to cued targets (commonly referred to as Inhibition of Return; IOR).
4. Three-way interaction between stimulation, task and cue – for the exogenous task IOR is expected. However, for the endogenous task, a facilitation effect is expected only for the beta and sham stimulation conditions but not for the alpha stimulation condition.

Lateralisation specific effects (see Fig. 2), analysed separately for endogenous & exogenous tasks.

5. Main effect of stimulation for both endogenous and exogenous tasks – RTs to all targets will differ for alpha and beta stimulation conditions (two tailed).
6. A main effect of cue for the endogenous task – RTs to cued targets will be faster compared to RTs to uncued targets (facilitation effect).
7. A main effect of cue for the exogenous condition – RTs to uncued targets will be faster compared to RTs to cued targets (IOR).
8. Three-way interaction for endogenous task only – a facilitation effect, faster RTs for cued compared to uncued targets, is expected for beta and sham for both contralateral and ipsilateral stimulations. However, for the alpha stimulation condition, RTs during contralateral stimulation only are expected to show a facilitation effect. Importantly, no differences between cued and uncued RTs during ipsilateral alpha stimulation are expected.

3. Methods

3.1. *Transparency statement*

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/

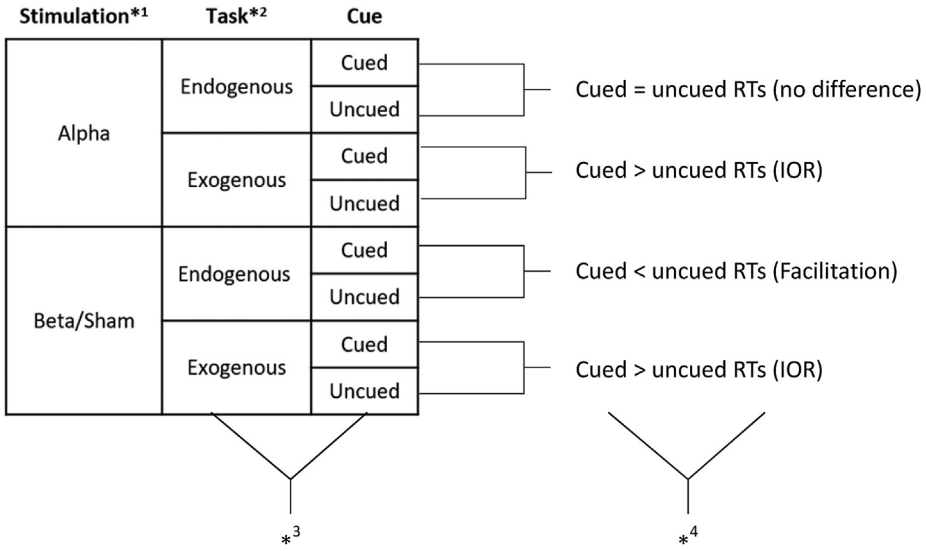

Fig. 1 – Diagram depicting the experimental factorial design: 3 (stimulation: alpha, beta, sham) × 2 (task: endogenous, exogenous) × 2 (cue: cued, uncued). Beta and sham stimulation conditions are collapsed for ease of display and because we expect the pattern of RTs to be the same for both; both are effectively control conditions. *1–*4: correspond to the numbered hypotheses, outlined above, and the numbered analyses outlined in the 'Behavioural data analysis' section.

exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

3.2. *Overview*

The study consisted of a pre-experiment in which EEG was recorded and analysed to determine participants' individualised alpha peak frequency. Following the pre-experiment, participants engaged in two behavioural tasks, one engaging endogenous and one exogenous tactile attention. During the two tactile attention tasks, tACS was administered. Each participant completed both behavioural tasks three times - during sham, alpha, and beta stimulation conditions. Participation in each condition was separated by a minimum of 12 h to avoid carry over effects of the stimulation. We were careful to ensure that any order was counterbalanced across participants and properly randomised. Full details of our randomisation and counterbalancing can be found under supporting documents in the 'Participant stimulation order' document (https://osf.io/kat3w). Specifically, the following parameters were counterbalanced across participants and session.

- Side of stimulation – whether tACS was applied over the left or right hemisphere throughout all experiments for one participant.
- Stimulation order – given three stimulation frequencies (alpha, beta, and sham) there were six possible stimulation orders; these were randomised across participants.
- First task – this was either the endogenous or exogenous task – this was randomised across participants for the first session; after that the sequence of tasks was counterbalanced within participants.
- Endogenous cue – single tap indicated attend left and double tap attend right for half of the participants. Counterbalanced across participants, for the other half, single tap indicated attend right and double tap attend left.

3.3. *Participants*

3.3.1. *Sample size estimation*

Few papers, using either attentional cueing paradigms or tactile perception with tACS, have reported effect sizes. This makes choosing an effect size, to conduct an *a priori* power analysis for sample size estimation, difficult. Importantly, however, our critical hypothesis (no. 4) is a three-way interaction between task (endogenous, exogenous), stimulation (alpha, beta, sham) and cue (cued, uncued) in a within-subjects design. We focus on this critical interaction to determine our sample size because it is the most theoretically interesting of our anticipated results, and because our own data (Jones & Forster, 2014) provide a solid basis for estimating power in this case.

We know of no off-the-shelf software offering a power analysis for the interaction in a repeated-measures ANOVA. G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) for example, does not. However, in the specific case of a repeated-measures factorial ANOVA with two levels per factor (as outlined in Fig. 1) any interaction becomes identical to a paired *t* test applied to an appropriate set of differences between conditions. Hypothesis four can thus be recast as a paired *t* test on the difference (alpha minus beta/sham) of differences (endogenous minus exogenous) between cuing effects (cued minus uncued conditions).

Data from Jones and Forster (2014) provide an estimate of what we should expect for the difference (endogenous minus exogenous) between cuing effects (cued minus uncued), but specifically in the case of no stimulation (which we equate to beta/sham in the proposed new experiment). In order to extrapolate from these data to the new design for the purposes of estimating power, we made the following assumptions/calculations.

1) The exogenous cuing effect (i.e., IOR) will be unaffected by alpha stimulation, but the endogenous cuing effect (i.e.,

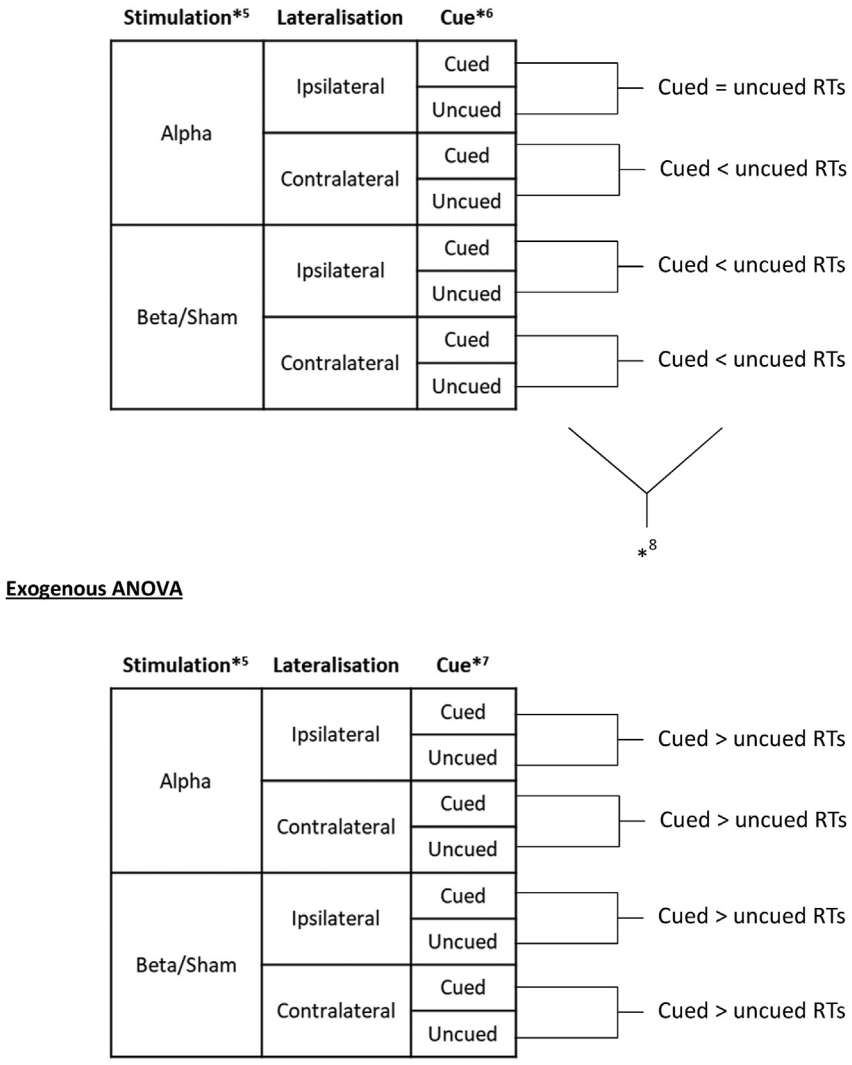

Fig. 2 – Diagram depicting the experimental factorial design: 3 (stimulation: alpha, beta, sham) × 2 (lateralisation: contralateral, ipsilateral) × 2 (cue: cued, uncued), for the endogenous (top) and exogenous (bottom) task separately. Beta and sham stimulation conditions are collapsed for ease of display and because we expect the pattern of RTs to be the same for both, both are effectively control conditions. *5–*8: correspond to the numbered hypotheses above, and the numbered analyses outlined in the 'Behavioural data analysis' section.

facilitation of RTs) will be reduced to zero. Although not a conservative assumption, we consider this reasonable in combination with:

2) The size of the difference between endogenous and exogenous cueing effects (i.e., the 2 × 2 interaction) under sham/beta stimulation can be estimated as the *lower bound* of the 95% confidence interval estimated for this same RT difference from the Jones and Forster (2014) data – this yields a conservative anticipated effect of (at least) 76 msec.
3) The corresponding effect under alpha stimulation will be driven by only the (unaffected) exogenous cuing effect, estimated from Jones and Forster (2014) as 20 msec.
4) The difference between the values determined in steps 2 and 3 (~56 msec) equates to the anticipated 2 × 2 × 2 interaction. To derive a measure of Cohen's D for this difference of differences between cuing effects, we must estimate the corresponding standard deviation. Here, we assume that under both alpha and beta/sham stimulation the SD of endogenous minus exogenous cuing effects will reflect that obtained without stimulation in Jones and Forster (2014). We then apply the variance sum law, with the conservative assumption of zero correlation between the difference scores that represent the 2 × 2 interaction in each half of the design (alpha vs. beta/sham).

By following these steps, we estimated a Cohen's D (for the difference score best representing the anticipated 2 × 2 × 2 interaction) of .376. This yields $N = 77$ to achieve 90% power with alpha set to .05. Participants who did not meet the

selection criteria or whose data was lost or damaged due to unforeseeable circumstances did not contribute to this sample size. Testing continued until we reached a sample of 77 useable participants which were included in the analysis. An additional 37 participants completed session one and/or two but did not complete all three sessions and could not be included in the analysis. Importantly, no analysis was conducted on the 37 participants at any time and did not form part of any results. The main reason for the high additional number of participants was the complexity of scheduling three sessions on separate days which was further complicated by the COVID-19 pandemic.

3.3.2. *Sample*

Participants were aged between 18 and 40 years ($M = 24.34$, $SD = 5.18$) and were all right handed (by self-report). No further demographic information was used as exclusion criteria. 33 men and 44 women took part in the study (by self-report). Participants were recruited via the University booking and recruitment system (SONA), by word of mouth, or advertising locally. Participants were asked to complete a tES safety screen questionnaire (see https://osf.io/p7ame/) which has been adapted from the Transcranial magnetic stimulation (TMS) Adult Safety Screen (TASS) questionnaire (Keel et al., 2001). Any 'yes' answer in the questionnaire resulted in a prospective participant not being able to take part in the study. Participants who took part in the study were reimbursed with Amazon vouchers for their participation at the rate of £9 per hour.

3.4. *Materials and apparatus*

Two connected PCs were used; one to present stimuli and record behavioural responses and a second to record EEG data. Tactile stimuli were presented using two tactors placed 60 cm apart in front of the participant connected to a TactAmp (Dancer Design, Ltd.). Tactile stimuli in the pre-experiment were presented using one tactor contralateral to that participant's to-be-stimulated hemisphere and in the main experiment to both left and right tactors. Headphones played white noise (at a comfortable listening level) to mask any sounds made by the tactors. RTs (in the main experiment) were recorded using a voice-key connected to the TactAmp. E-Prime v.3 (Psychology Software Tools) software was used for stimulus presentation and to record behavioural responses. Black fabric was used to cover participants' hands throughout the experiment, to avoid visual input of the stimulated site (Sambo, Gillmeister, & Forster, 2009). During the pre-experiment, Electroencephalography (EEG; BioSemi Active Two system) was recorded from 64 active electrodes on the scalp with a sampling rate of 2048 Hz. Two Vertical electro-oculogram electrodes (VEOG) were placed above and below the right eye. The standard BioSemi reference, Common Mode Sense (CMS) electrode and Driven Right Leg (DRL) electrode was used during recording. tACS stimulation was delivered by a DC-Stimulator Plus (neuroConn©). For tACS two 70 × 50 mm rubber electrodes were used, held in place on the scalp using a Velcro® strip and conductivity was increased using a Ten20 Conductive paste.

3.4.1. *Pre-experiment*

3.4.1.1. Design and procedure. The primary purpose of the pre-experiment was to identify a participants' peak alpha frequency during tactile perception. We used a similar paradigm for stimulus presentation as used by Gundlach et al. (2016). Participants passively received repetitive tactile stimuli to one finger during which EEG was recorded. The tactile stimuli were 100 msec in duration and presented at supra-threshold intensities, which feels like a quick tap to the finger. All tactile stimuli in the pre-experiment were presented to either the participant's left or right index finger. Importantly, if a participant was assigned to receive tactile stimulation to their index finger on their right hand the subsequent tACS was over their left hemisphere, and vice versa (the left-right allocation was counterbalanced across participants, see https://osf.io/p7ame/: 'Participant stimulation order'). Over two blocks, with a short break in the middle, 150 stimuli were presented to each participant with a mean inter-stimulus interval of 2050 msec and a maximum jitter of 900 msec. A fixation cross was presented on a monitor throughout the testing. Prior to tactile presentation, participants were asked to blink 10 times (prompted by a visual cue on the monitor) during which EEG data was also recorded; this interval was used for ocular correction.

3.4.1.2. EEG recording and analysis pipeline. Data were immediately analysed offline via a pre-programmed analysis pipeline (Brain Vision Analyzer 2; see https://osf.io/p7ame/'EEG analysis pipeline for peak alpha.ehtp' for script). Raw data were filtered using a .1 high- and 40 Hz low-pass zero-phase-shift Butterworth filters, as well as a 50 Hz notch filter. Bad channels were replaced using topographical interpolation, limited to maximum of five channels in total and electrodes which were used for subsequent analysis were not interpolated (i.e., C3 and C4). Data were re-referenced to a common average. Ocular correction Independent Component analysis (ICA), based on the blink time interval, was applied to the data set to reduce eye-blinks. Data were segmented into 3000 msec long epochs, 1500 msec before and 1500 msec after stimulus onset. A 100 ms pre-stimulus baseline correction was applied. Trials including artefacts, ±100 μV at any electrode were marked as bad and not analysed. Time-frequency analysis was run on the data which had not been baseline corrected, but excluding bad segments. A Complex Morlet wavelet analysis was used ($c = 5$) in the frequency interval between 5 and 20 Hz, in 150 linear frequency steps (at increments of 0.1 Hz). The wavelets analysis was baseline corrected from −600 to 200 msec pre-stimulus interval, avoiding border and smearing effects. The output was spectral amplitude (μV). The data was then averaged across trials and conditions and exported to Matlab where the peak individualised alpha frequency was determined (see https://osf.io/p7ame/: IndividualFrequency.m for this Matlab script). A peak alpha frequency for an individual participant was defined as the frequency that contains the lowest spectral amplitude, within a given time window, at the electrode over the somatosensory cortex contralateral to the hand to which stimuli were presented. As in previous research (Gundlach et al., 2016) a search for the lowest amplitude will be restricted to a time window between

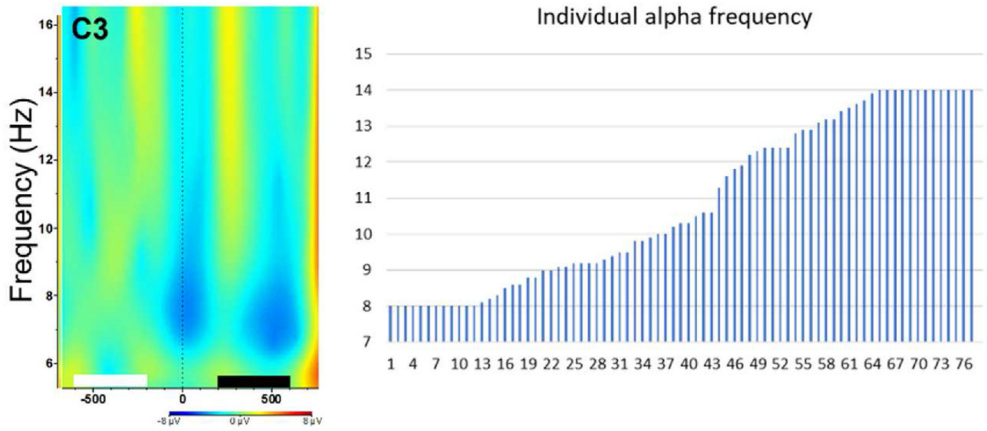

Fig. 3 – *Left*. Average wavelet for the individualisation task for electrode C3 (tactile target to the right hand). Time 0 (*x* axis) represents the onset of the tactile stimulus. The white bar represents the baseline interval (−200 to −600 msec) and the black bar the interval in which individualised alpha frequency was chosen (200–600 msec). *Right*. The individualised alpha frequency for each participant.

200 and 600 msec after stimulus onset and a frequency range of 8–14 Hz (see Fig. 3). Unlike previous research (Gundlach et al., 2016) data were not averaged in the time domain as this reduces resolution and may hide peak frequency changes, rather the minimum amplitude (i.e., largest negative value) in a single time point and frequency was identified. This frequency was used as the individuals' alpha frequency for tACS.

3.4.1.3. EEG REJECTION CRITERIA. Participants were screened and would have been excluded from taking part in the main experiment if, after taking part in the EEG experiment a peak frequency could not be defined. Specifically, after the data was pre-processed and an event-related time-frequency decomposition of the signal had been completed, if none of the frequencies (between 8 Hz and 14 Hz in .1 Hz intervals) had a value lower than zero between 200 msec and 600 msec, at contralateral electrode C3/C4, then the participant was to be excluded from taking part in the main experiment. Furthermore, if, after excluding trials from further analysis based on artefactual contamination (ocular muscular activity or other) fewer than 40% of trials (i.e., 60 trials) were available to contribute to the time frequency analysis the participant would have been excluded from further participation. However, zero participants were excluded on this basis.

3.4.2. *Main experiment*

3.4.2.1. MAIN EXPERIMENT – TACS. All participants completed all stimulation conditions; real-alpha, real-beta and sham stimulation, the order counterbalanced across participants. Stimulation conditions were separated by at least 12 h so as to prevent any possible carry-over effects of the stimulation. Participants were allocated to a right or left hemisphere stimulation group, counterbalanced across the sample. This was randomly assigned using KUTOOLS™ 'Insert random data' function in Excel (see https://osf.io/p7ame/: 'Participant stimulation order. xlsx' for further details). Sham stimulation involved the application of a current for 30 s as it ramps to its full current density when it was then turned off (see Siebner et al., 2004). Double blinding in a repeated-measures design where frequency of stimulation needs to be set by the experimenter is not possible. However, measures were taken to ensure that the participant was blind to the stimulation protocol being used. Specifically, in all conditions the placement of electrodes on the scalp was identical and stimulation (alpha, beta or sham) was only started once the participant was in position to respond to the tactile stimuli. The only possible information during testing which could have been used by the participant to understand which stimulation condition they were undergoing is the display of the tACS stimulation machine. To avoid this, the stimulation machine was placed behind the participant and the screen of the device was covered. Furthermore, after each experimental session participants were asked whether they felt the stimulation was real or fake. If, overall, participants perform significantly above chance in their guessing, participant awareness of stimulation should be considered as a possible mechanism for action in our interpretation of the findings.[3] In the real-alpha condition, participants had tACS, to their left or right hemisphere depending on group, at individualised alpha frequencies. Real-beta stimulation was set at 25 Hz and presented to the same hemisphere as in the alpha stimulation and sham conditions. One electrode (70 × 50 mm) was placed at 10–20 location CP3 (left) or CP4 (right) and the second electrode (70 × 50 mm) was placed at 10–20 location FP1 (left) or FP2 (right) (see Fig. 4). The frontal electrode was orientated such that the 70 mm side was parallel with the midline whereas the parietal electrode was orientated such that the 50 mm side was parallel with the midline. Location and orientation of the electrodes were decided upon after modelling current flow using specialised software (HD Explore Soterix Medical Ltd; see details below of modelling procedure). A current of 2 mA, peak to peak, was applied (maximum current density of .5714 A/m^2). Stimulation was applied whilst

[3] 17 out of our 77 participants correctly identified all three of their sessions as either sham or real stimulation. Given our results showed no effect of stimulation condition (main or interactions) we did not further investigate whether this was statistically significantly above chance.

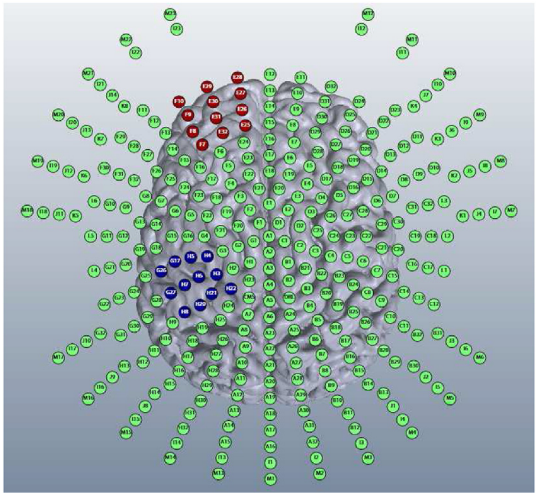

Fig. 4 – Placement of electrodes on the surface of the scalp for use in modelling current flow. 12 ring electrodes are used an approximation for 70 × 50 mm pad electrodes.

participants completed the main experiment. The main experiment consisted of an endogenous and exogenous tactile attention task; the specific sequence of events for each task and trial is outlined below. Stimulation started after participants completed the practice trials for each task and approximately 1 min before the main experimental tasks in order to check the participant was comfortable and to allow for oscillatory entrainment. Stimulation was stopped once the participant completed the task but was set at a maximum of 30 min per task. This resulted in a maximum of 1-h stimulation per day. This is within the recommended safety limits for stimulation in a day (Antal et al., 2017) and means participants were stimulated during the whole behavioural paradigm. Stimulation was stopped and restarted again, in between experimental tasks. Over three days participants experienced a maximum of 120 min of real tACS.

3.4.2.2. Field intensity modelling. We simulated theoretical models of current flow patterns in an example 'standard' brain using specialised software (HD-Explore, Soterix Medical). Multiple considerations of electrode placement configurations on the scalp were simulated and field intensity was computed based on the model. Our primary aim was to achieve a maximal field intensity at the peak voxel of the primary somatosensory cortex over one hemisphere (±39,−24,59) as defined by activation likelihood estimations (Mayka, Corcos, Leurgans, & Vaillancourt, 2006). Second, we aimed to ensure limited current field intensity over the same coordinates over the opposite hemisphere, in order to ensure stimulation of the primary somatosensory region was uni-hemispheric. Finally, we wanted to ensure minimal current field intensity over the visual cortex, given the role of alpha oscillations in visual processing (± 11, 81,7; Lacadie, Fulbright, Arora, Constable, & Papademetris, 2008). An approximation of the stimulation delivered via 50 × 70 mm electrodes was achieved by selecting 12 ring electrodes on a 322-electrode montage (see Fig. 4). The criteria were best met when one pad electrode was modelled at electrode location Cp3 and the other at electrode location Fp1 (for the left hemisphere). The frontal electrode was orientated such that the 70 mm side was parallel with the midline whereas the parietal electrode was orientated such that the 50 mm side was parallel with the midline. These parameters resulted in a field intensity of .229 V/m at the peak-voxel of the primary somatosensory cortex on the left hemisphere, .105 V/m at the peak-voxel of the primary somatosensory cortex on the right hemisphere and .103 V/m and .120 V/m over the left and right primary visual cortices respectively (see Fig. 5 for current intensity maps). Although current, and subsequently field strength intensity, is widely distributed throughout the cortex, these models allow us to claim with some confidence that the primary somatosensory cortex is being manipulated uni-hemispherically and more so than primary visual areas with our electrode montage. Although, models based on standard brain types are likely to differ from individuals' cortical structure – this modelling informs our methodological approach but does not provide precise current flow maps.

3.4.2.3. Behavioural tasks. Participants received stimulation (for each condition; alpha, beta and sham stimulation) while they concurrently completed an endogenous and exogenous cue-target task. The order of the tasks was counterbalanced across stimulation conditions and participants. To minimise practice effects, the order of the first task was alternated. If a participant started their first session with the exogenous task, then their second session began with the endogenous task, and their third the exogenous task again (see https://osf.io/p7ame/: 'Participant stimulation order. xlsx').

Before each task in session one the participants engaged in two short practice blocks which were not analysed. In both tasks each practice block consisted of 19 trials. In the endogenous task each block had 12 cued, 4 uncued, 2 catch trials, 1 fast filler trials. In the exogenous task each block was made up of 8 cued, 8 uncued, 2 catch and 1 fast filler trials. Any practice effect of speeding up RTs in the subsequent session has shown to be greatly reduced after six trials in a simple reaction time task (Collie, Maruff, Darby, & McStephen, 2003). Therefore, to increase the reliability of RTs across different testing sessions one practice block was also included before each task in each of sessions two and three.

3.4.2.4. Endogenous orienting task. Each trial started with a 100 msec tactile cue to the index fingers of both hands (see Fig. 6 for a schematic representation of events in a trial). The bilateral cue was either a 100 msec single tap or a double tap (two 40 msec taps with a 20 msec inter-stimulus interval; ISI). For half the participants, the single tap indicated to attend left and double tap to orient attention to the right hand, the association was reversed for the other half (see https://osf.io/p7ame/: 'Participant stimulation order.xlsx' for further details). After an ISI of 900 msec a target (100 msec single tap) appeared to either the cued (75%) or uncued (25%) hand. Participants were explicitly informed that they should use the cues to shift their attention and expect the target at the cued hand, and that this would speed up their RTs. The target was unilaterally presented to either the left or right index finger. Once the participant detected the target they responded by saying 'pa' into a microphone. Following the response, a

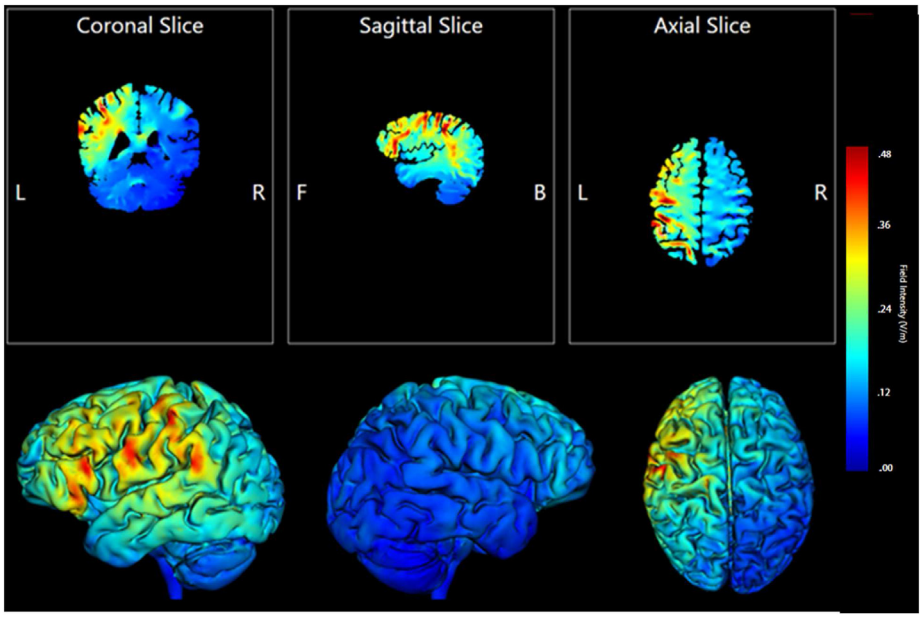

Fig. 5 – Simulation of current field intensity in the brain based on specified electrode locations (see Fig. 4) with 2 mA input. *Top*: 2D Slices are centred around the peak voxel of the primary somatosensory cortex (+/39, −24, 59). *Bottom*: 3D model of simulation of current field intensity in the brain, left: left hemisphere, middle: right hemisphere, right: top view of cortex with frontal lobe at the top.

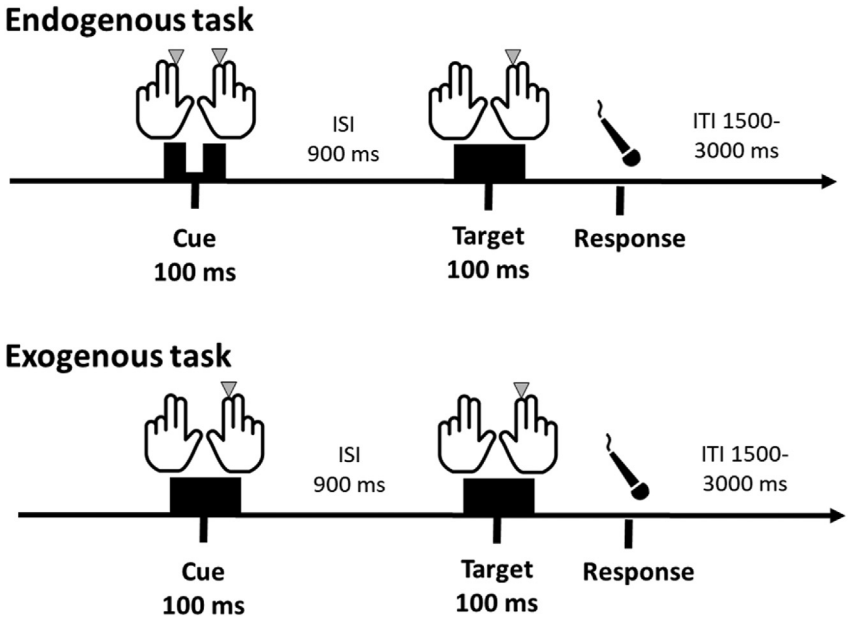

Fig. 6 – Schematic representation of events in a trial. In the endogenous task (top) the cue was bilaterally presented to the index fingers of both hands. The cue was either a 100 msec single tap or double tap (pictured above). The cue was informative of the likely location of the upcoming target. In the exogenous task (bottom) the cue was a 100 msec single tap to either the left or right index finger and not informative of the target location. ISI – inter stimulus interval; ITI – inter trial interval.

random inter-trial interval (ITI) of 2000–3000 msec was included before the next trial started. If no response was made within 2000 msec the ITI commenced. A fixation cross was presented throughout the trial. 10.5% of trials were catch trials where a cue but no target was presented, requiring no response. Moreover, 5% of trials were "fast filler" trials where the interval between cue and target was 400 msec. Fast filler trials were not analysed but were included to reduce the anticipation of target presentation and together with catch trials reduce the possibility that responses are automatically

made without the target first being processed (see Jones & Forster, 2014 for a similar design and procedure). The endogenous task consisted of 4 blocks of 76 trials. Each block consisted of 48 cued, 16 uncued, 8 catch, and 4 fast filler trials. In between each block participants took a short break and feedback in terms of overall RTs and any errors made was presented to the participant.

3.4.2.5. Exogenous orienting task. The same procedure was included in the exogenous task with the following exceptions. The cue was a 100 msec single tap only and presented unilaterally. The exogenous task consisted of 4 blocks of 76 trials. Each block consisted of 32 cued, 32 uncued, 8 catch, and 4 fast filler trials. The participants were explicitly informed that the cue does not predict the target location.

3.4.2.6. Behavioural rejection criteria. Trials with RTs less than 100 msec (from stimulus offset) and greater than 2 standard deviations above each participant's overall mean in each task (excluding catch and fast filler trials), were excluded from analysis. Further, trials including a response in the interval between cue and target were excluded as well as if no response was detected as this was labelled as a missed target. If any of these conditions exceeded 15% of the total trials then the participant's data was excluded from the group analysis. Catch trials: If the participant accidently responded to a catch trial when no response was required in 50% or more of catch trials this participant was excluded from the group analysis. This rejection on the basis of behavioural responses was aimed at excluding participants who did not fully understand or engage in the tasks.

3.5. *Behavioural data analysis*

Behavioural data were analysed using three separate repeated measures analysis of variances (ANOVAs), with RTs as the dependent variable for all. First, we examined task-specific effects by analysing data using a 2 × 2 × 3 repeated measures ANOVA with the factors Task (endogenous, exogenous), Cue (cued, uncued), Stimulation condition (alpha, beta, sham). Data were also analysed using two separate three-way repeated measures ANOVAs, one for the endogenous task and one for exogenous task. The specifics of the analyses are presented below, and numbers correspond to the predictions outlined in the 'Hypotheses section' above.

3.5.1. *Task specific effects*

1. Significant main effect of Stimulation condition in ANOVA
   a. Three planned paired *t* tests expected to show RTs to: alpha < sham; beta < sham; no difference between beta and alpha (confirmed by Bayes factor; $BF_{10} \leq 1/3$).
2. Significant main effect of Task, RTs in the exogenous task expected to be faster than those in the endogenous task.
3. Significant interaction between Task and Cue.
   a. Two planned paired *t* tests should show faster RTs to cued compared to uncued targets for the endogenous task. However, in the exogenous task, planned paired *t* tests should show faster RTs to uncued compared to cued targets.
4. Significant three-way interaction between Stimulation condition, Task and Cue. Further analysis by the following six planned paired *t* tests:
   a. In the sham and beta conditions for the exogenous task, *t* tests should show faster RTs to uncued compared to cued targets.
   b. In the sham and beta conditions for the endogenous task, *t* tests should show faster RTs to cued compared to uncued targets.
   c. In the alpha stimulation condition for the exogenous task a *t* test should show faster RTs to uncued compared to cued targets.
   d. In the alpha stimulation condition for the endogenous task a *t* test should show no significant difference between RTs to cued compared to uncued targets (confirmed by Bayes factor; $BF_{10} \leq 1/3$).

3.5.2. *Lateralisation specific effects*

The analysis of the endogenous and exogenous task separately includes testing for lateralisation specific effects also. In this analysis, lateralization refers to the relationship between the cue side and stimulated hemisphere. Given that we counterbalanced across participants which side of the brain was targeted by the stimulation, we had two groups of participants - left vs. right hemisphere stimulated. In the endogenous task the cue was presented bilaterally, and the cue side refers to the side to which the participant was to orient their attention. In the exogenous task, the cue was presented unilaterally, and the cue side refers to the actual side the cue appeared. In the endogenous task, for those stimulated on the right side, ipsilateral stimulation refers to cues directing attention to the right hand; targets appearing to the left are uncued but those on the right are cued. For those same participants stimulated on the right side, contralateral stimulation refers to cues directing attention to the left hand; targets appearing to the right are uncued but those on the left are cued. The reverse is true for those participants who were stimulated on the left side of the head. In the exogenous task, for those stimulated on the right side, ipsilateral stimulation refers to cues appearing to the right hand; targets appearing to the left are uncued but those on the right are cued. For those same participants stimulated on the right side, contralateral stimulation refers to cues appearing to the left hand; targets appearing to the right are uncued but those on the left are cued. Each task was analysed using a 2 × 2 × 3 repeated-measures ANOVA with the factors Lateralisation (contralateral, ipsilateral), Cue (cued, uncued) and Stimulation condition (alpha, beta, sham). We made the following analysis plan.

5. Both exogenous and endogenous ANOVAs should show a significant main effect of Stimulation condition:
   a. Three planned paired *t* tests for both the exogenous and endogenous tasks should show RTs to targets such that: alpha < sham, beta < sham, no difference between beta and alpha (Bayes factor; $BF_{10} \leq 1/3$)
6. A main effect of Cue for the endogenous condition is expected, such that cued targets have faster RTs compared to uncued targets – a facilitation effect.

7. A main effect of Cue for the exogenous condition is expected, such that cued targets have slower RTs that uncued targets an IOR effect.
8. A three-way interaction for the endogenous ANOVA only is expected, such that a facilitation effect (faster RTs to cued compared to uncued targets) should be eliminated for alpha ipsilateral stimulation only. Demonstrated by six planned paired *t* tests:
   a. In the sham and beta conditions during contralateral and ipsilateral stimulation, *t* tests should show faster RTs to cued targets compared to uncued targets.
   b. In the alpha stimulation condition during contralateral stimulation *t* tests should show faster RTs to cued compared to uncued targets.
   c. In the alpha stimulation condition during ipsilateral stimulation *t* tests should show no significant difference between RTs to cued compared to uncued targets (Bayes factor; $BF_{10} \leq 1/3$).

Bayes factor analysis was additionally computed for non-significant effects ($p \geq .05$) and Bayes Factor values less than 1/3 were used to indicate support for the null hypothesis (Dienes, 2014). Significant effects were interpreted based on *p*-values to be comparable with the literature.

3.5.3. *Alternative analysis for hypothesis 8*

We also defined alternative hypotheses to test cue-side relative to stimulation side lateralisation effects. Although we set out an analysis procedure that tests our prediction that ipsilateral changes in alpha power modulate attentional allocation for the endogenous task, we were clear in the introduction that this is an open question. It is possible that alpha modulations contralateral to the cued side drive attentional processes or that it is a mixture of both. Therefore, we have set out an alternative analysis procedure for hypothesis 8 that should be able to disentangle these different models.

If contralateral decreases in alpha power drive attention allocation, the following analysis should confirm the model.

1. A three-way interaction for the endogenous ANOVA only is expected, such that a facilitation effect (faster RTs to cued compared to uncued targets) should be eliminated for alpha contralateral stimulation only. Demonstrated by six planned paired *t* tests:
   a. In the sham and beta conditions during contralateral and ipsilateral stimulation, *t* tests should show faster RTs to cued targets compared to uncued targets.
   b. In the alpha stimulation condition during ipsilateral stimulation *t* tests should show faster RTs to cued compared to uncued targets.
   c. In the alpha stimulation condition during contralateral stimulation *t* tests should show no significant difference between RTs to cued compared to uncued targets (Bayes factor; $BF_{10} \leq 1/3$).

If a mixture of contralateral decreases, and ipsilateral increases, in alpha power both drive the allocation of attention, the following analysis should confirm the model.

2. A two-way interaction for the endogenous ANOVA only is expected, such that a facilitation effect (faster RTs to cued compared to uncued targets) should be present for all types of stimulation but diminished for alpha ipsilateral and contralateral stimulation. Demonstrated by planned paired *t* tests:
   a. In the sham, beta and alpha stimulation conditions, during contralateral and ipsilateral stimulation, *t* tests should show faster RTs to cued targets compared to uncued targets.
   b. The facilitation effect (uncued RT − cued RTs) should be greater in sham and beta stimulation compared to alpha (both ipsilateral and contralateral) stimulation.

4. Results

To briefly summarise the results, there was a significant facilitation of RTs in the endogenous task and IOR in the exogenous task replicating previous findings (see Fig. 7). There were no effects of stimulation indicating that tACS had no effect on either orienting of endogenous or exogenous attention. The results below are listed and numbered in correspondence to the hypotheses above. For raw data, averaged data, and analysis results files, see https://osf.io/p7ame/.

4.1. *Task specific effects*

1. There was no main effect of Stimulation ($F(2,152) = .035$, $p = .950$, $\eta_p^2 < .001$) indicating RTs did not differ across alpha, beta and sham conditions. This null finding was confirmed by the Bayes Factor analysis showing a strong support for the null hypothesis ($BF_{10} = 5.789 \times 10^{-11}$).
2. There was a main effect of Task $F(1, 76) = 30.06$, $p < .001$, $\eta_p^2 = .283$ where RTs in the endogenous ($M = 551.79$, $SE = 20.74$) task were significantly faster compared to the exogenous task ($M = 586.73$, $SE = 21.92$). This effect was the opposite to what was predicted as one of the outcome neutral effects.
3. There was a significant interaction between Task and Cue ($F(1, 76) = 30.92$, $p < .001$, $\eta_p^2 = .289$) and planned follow up analysis for each task separately showed, as predicted, RTs to be facilitated in the endogenous task ($t(76) = -3.76$, $p < .01$) as cued targets were faster than uncued targets (Cued $M = 547.14$, $SD = 182.32$, Uncued; $M = 556.43$, $SD = 182.27$). Moreover, as predicted we observed significant IOR in the exogenous task ($t(76) = 5.81$, $p < .001$) as cued targets ($M = 593.09$, $SD = 192.42$) were slower than uncued targets ($M = 580.37$, $SD = 192.72$) (see Fig. 7).
4. There was no Task*Cue*-Stimulation interaction ($F(2, 152) = .21$, $p = .182$, $\eta_p^2 = .003$, $BF_{10} = .047$), moderate to strong support for the null hypothesis.

4.2. *Lateralisation specific effects*

Our lateralisation analysis was aimed at exploring the relative relationship between the side of the head stimulated and the side where the cue appeared (exogenous task) or attention was oriented (endogenous task).

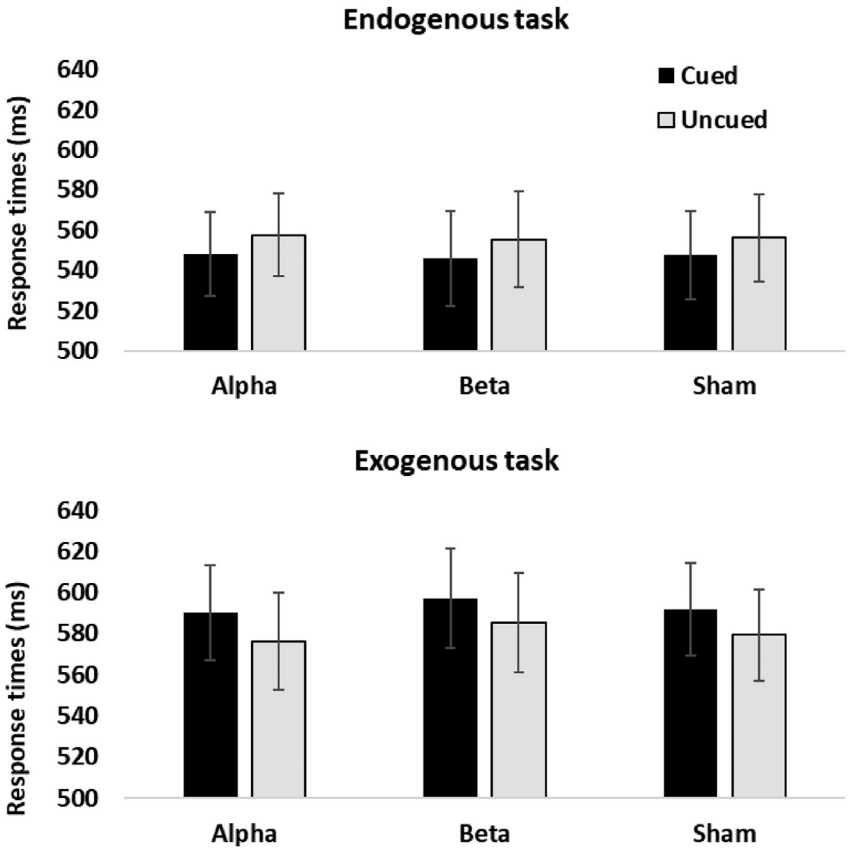

Fig. 7 – Average response times (in milliseconds) for the endogenous and exogenous tasks for each of the stimulation conditions. There was an overall significant facilitation effect in the endogenous task as cued (black) responses were faster compared to uncued (grey) responses. In the exogenous task there was inhibition of return (IOR) when the target was presented to the same side as the cue (cued) response times were slower compared to when the cue and target were presented to different sides (uncued). Error bars are Standard Error of the mean.

5. There was no main effect of Stimulation in either endogenous (F (2, 152) = .013, p = .987, η_p^2 <.001, BF_{10} = .013) or the exogenous task (F (1.8, 133.2) = .188, p = .829, η_p^2 = .002, BF_{10} = .016) which is in line with the Task specific results 1) above. Bayes Factor analysis suggest strong support for the null for both hypotheses. That is, RTs did not differ as a function of tACS stimulation in either the endogenous or exogenous task.
6. There was a facilitation effect of RTs in the endogenous task, see Result 3 above.
7. There was an IOR effect in the exogenous task, see Result 3 above.
8. For the endogenous task, there was no Lateralisation*Cue*Stimulation condition interaction (F (2, 152) = .559, p = .573, η_p^2 = .007, BF_{10} = .040), strong to moderate support for the null hypothesis. Thus, no justification for further t tests. Given support for the null hypothesis, and a non-significant three-way interaction, there was no need to conduct the Alternative analysis for hypothesis 8.

4.3. *Exploratory analyses*

There is evidence to suggest that alpha activity over the left and right hemispheres are different and may result in different spatial attention effects (Lasaponara, Pinto, Aiello, Tomaiuolo, & Doricchi, 2019; Thut et al., 2006). To explore this in the somatosensory domain we divided the data into two groups. Those participants who received tACS stimulation over the left (n = 37) and right (n = 40) hemisphere and ran the Lateralisation specific effects analysis, described above separately for each group, with an adjusted significance criterion of p < .025 for each analysis. Similar to results 6 above, there was facilitation of attended targets in the endogenous task for participants who received both left (F (1, 36) = 8.62, p = .006, η_p^2 = .193) and right hemisphere (F (1, 39) = 7.23, p = .010, η_p^2 = .156) stimulation. There were no other significant effects (all p's > .076, and F's < 2.65). Similar to result 7 above, there was significant IOR for participants who received left (F (1, 36) = 26.60, p < .001, η_p^2 = .425) and right hemisphere stimulation (F (1, 39) = 12.09, p = .001, η_p^2 = .237). There were no other significant effects in the exogenous task for right or left stimulation (all F's > .174 and F's < 1.79).

5. Discussion

This registered report aimed to investigate if presenting tACS at alpha frequency influenced participants' orienting of tactile attention. We observed facilitation of response times in the

endogenous task and IOR in the exogenous task. However, we observed no effect of tACS. Response times and attention effects did not differ as a result of tACS at either alpha or beta frequencies compared to sham. This well powered study, conducted over three separate days, suggests that lateralised tACS at the alpha frequency has no observable effect on endogenous and exogenous tactile attentional processes. Support for the null hypothesis leads us to two possible conclusions that we consider in detail here. First, that lateralised alpha power in the cortex is not causally related to attentional processes. Second, that tACS is unable to effectively manipulate lateralised alpha power that has a describable effect on exogenous and endogenous orienting.

The behavioural effects in each task replicated previous findings of tactile attention, with facilitation of cued/attended compared to uncued/unattended targets observed in the endogenous task, and IOR in the exogenous task (e.g., Jones & Forster, 2014; Lloyd et al., 1999; Silas et al., 2019; Spence & Gallace, 2007). These outcome neutral behavioural effects were predicted and provide evidence that the participants engaged in the task and that attention was allocated effectively. We also predicted that RTs in the exogenous task would be faster than the endogenous task. However, we observed the opposite, with faster RTs in the endogenous compared to exogenous task. This prediction was largely based on studies in visual attention which have suggested spatial attention is oriented faster when it is directed exogenously (by using peripheral cues) than endogenously (by using central cues) (Berger et al., 2005; Müller & Rabbitt, 1989). However, this prediction was in hindsight less well founded as more similar tactile attention studies have shown no difference in overall RTs between exogenous and endogenous orienting (Jones & Forster, 2014; Silas et al., 2019). A direct comparison between the two tasks is of less relevance here and any overall effect is dependent upon specific task variables (Chica et al., 2014). Our final outcome neutral prediction was the expected main effect of tACS on RTs, for this we found very strong support for the null hypothesis. Given the strong support for there being no difference in RTs as a function of the stimulation condition it leads us to seriously consider the possibility that tACS is having no effect on the underlying cortical systems we are attempting to modulate. We consider this possibility in more detail after our consideration of the causal link between alpha oscillations and attention.

Given the strong support for the null, the careful and systematic process of pre-registration, and the large sample of our study, it is appropriate for us to consider that tactile attentional processes are not causally related to lateralised alpha power in somatosensory cortex. Indeed, this is an ongoing debate in the literature that has recently been given some attention (e.g., Peylo, Hilla, & Sauseng, 2021). Whilst previous research has already contributed to this debate, we are the first to do so whilst exploring both endogenous and exogenous attentional tasks and within the somatosensory system. Recent research has also shown that alpha may have no relationship to attentional resources (Gundlach, Moratti, Forschack, & Müller, 2020). In a visuospatial task, Gundlach et al. (2020) demonstrate that attentional task demands independently modulate steady-state visual evoked potentials (SSVEPs) and alpha, suggesting that sensory gain in attentional orientation is not linked to alpha power. Similarly, Antonov, Chakravarthi, and Andersen (2020), again in the visual modality, show that changes in alpha amplitude do not precede changes in SSVEPs in cue-target intervals suggesting that alpha modulations are the result of attentional mechanisms, not causally influencing them. We add to this evidence and suggest that in tactile attentional processes, for both the orienting of endogenous and exogenous attention, lateralised alpha power changes observed in EEG are not causally related to attentional processes.

If attentional processes aren't causally linked to alpha power modulations, one might reasonably ask what cognitive processes do the observed alpha power modulations, reliably seen in attentional paradigms, reflect (Jensen & Mazaheri, 2010; Kelly et al., 2009; Rihs et al., 2007; Thut et al., 2006; Worden et al., 2000)? Whilst any position we here provide is speculative one possibility is that attentional processes are more closely linked to the phase of ongoing alpha oscillations and not the overall power or amplitude. We are aware that tactile stimuli presented near perceptual thresholds don't seem to be affected by alpha power and only by phase as modulated by tACS (Gundlach et al., 2016). One mechanism whereby alpha is said to modulate attentional processes is via modulation of sensory gain (Ikkai et al., 2016). In this respect, future analyses may consider examining the tACS phase at which tactile stimuli were presented in order to observe an effect on attention.

Given our null finding, although obtaining strong evidence for it, we are limited in our capacity to draw inferences from the data. However, an alternative explanation of our findings is that tACS did not effectively modulate the intended cortical areas. There is some support for the idea that alpha does not implement gain control in primary cortical areas but rather, via the fronto-parietal attention network (Zhigalov & Jensen, 2020). However, recent studies which have specifically targeted the fronto-parietal attention network using alpha-tACS have failed to find effects on spatial attention (e.g., Coleda et al., 2021; Van Schouwenburg, Sörensen, De Klerk, Reteig, & Slagter, 2018). Further, recent concerns have been raised regarding questionable research practices in the field of electrical non-invasive brain stimulation (Héroux, Loo, Taylor, & Gandevia, 2017; Bikson et al., 2018). In some cases, this has led authors to questions the ability for non-invasive electrical brain stimulation to effectively modulate behaviour (Héroux et al., 2017). What previous papers have argued is for open, transparent, and reproducible science to be at the forefront of further investigating cognitive or clinical aspects of the brain with non-invasive electrical brain stimulation. We agree strongly with this assertion and hope our registered report, with open materials and data, contributes in some way to better understanding of the effectiveness of tACS.

Finally, it must be considered that the null findings are a product of task procedure or set up. The alpha tACS stimulation was based on individualised alpha frequency for each participant. The distribution of peak frequencies was broad spanning the full 8–14 Hz scale, rather than a normally distribution around 10 Hz. Research has shown that the individualised peak alpha frequency can be modulated by a number of factors including changes over time (e.g., Benwell et al., 2019; see Mierau, Klimesch, & Lefebvre, 2017 for a

review). As this study lasted over three sessions, with the EEG recording and peak alpha frequency determined in the first session, this could have contributed to the effectiveness in stimulation. Future studies may wish to adopt a different approach to individualising alpha or just stimulating at a fixed frequency (e.g., 10 Hz). Other task parameters include tACS stimulation intensity and electrode location. It is not safe to stimulate at a higher amplitude but future studies may wish to use targeted electrodes which provide a more localised tACS signal.

To summarise, our findings demonstrate that individualised and lateralised alpha tACS targeting sensorimotor cortex has no effect on exogenous or endogenous tactile attentional mechanisms. We believe this contributes to the ongoing debate about the role of alpha in attentional processes and suggest that these findings support an account of alpha power not being casually involved in attention. Finally, we hope our open science approach to this research question contributes more broadly to better understanding the effectiveness of non-invasive electrical brain stimulation.

Open practices

The study in this article earned Open Data, Open Material and Preregistered badges for transparent practices. The data, materials and preregistered studies are available at: https://osf.io/p7ame/

Credit Author statement

Jon Silas - Conceptualization; Formal analysis; Methodology; Project administration, Funding acquisition; Writing - original draft; Writing - review & editing. Visualization; Supervision; Software.

Alexander Jones - Conceptualization; Formal analysis; Methodology; Project administration, Funding acquisition; Writing - original draft; Writing - review & editing. Visualization; Supervision; Software.

Kielan Yarrow - Conceptualization; Formal analysis; Writing - Original Draft.

Wayne Anderson - Investigation; Formal analysis; Project administration; Software; Writing - Original Draft.

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