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Differential effects of 10-Hz and 40-Hz transcranial alternating current stimulation (tACS) on endogenous versus exogenous attention

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ABSTRACT

Previous electrophysiological studies implicate both alpha (8–12 Hz) and gamma (>30 Hz) neural oscillations in the mechanisms of selective attention. Here, participants preformed two separate visual attention tasks, one endogenous and one exogenous, while transcranial alternating current stimulation (tACS), at 10 Hz, 40 Hz, or sham, was applied to the right parietal lobe. Our results provide new evidence for the roles of gamma and alpha oscillations in voluntary versus involuntary shifts of attention. Gamma (40 Hz) stimulation resulted in improved disengagement from invalidly cued targets in the endogenous attention task, whereas alpha stimulation (10 Hz) had no effect on endogenous attention, but increased the exogenous cuing effect. These findings agree with previous studies suggesting that right inferior parietal regions may be especially important for the disengagement of attention, and go further to provide details about the specific type of oscillatory neural activity within that brain region that is differentially involved in endogenous versus exogenous attention. Our results also have potential implications for the plasticity and training of attention systems.

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Attention; tACS; stimulation; plasticity; parietal; angular gyrus

Introduction

Selective attention refers to the ability to focus on a small subset of the myriad of stimuli and thoughts available to us at any moment. Studies of patients with hemispatial neglect have provided the valuable insight that lesions to the posterior parietal cortex can significantly impair processes of attention (Mesulam, 1981; Ro & Rafal, 1996). These patients have been found to be particularly impaired in responding to target stimuli in their neglected field after attention has just previously been directed to a location in their good visual field, suggesting that a specific deficit in the disengagement and reorienting of attention underlies hemispatial neglect (Posner, Walker, Friedrich, & Rafal, 1984). Although studies of patients with brain lesions provide crucial insights into the brain regions underlying cognitive functions, noninvasive brain stimulation has emerged as an important research tool that can overcome some of the limits of patient studies. By directly modulating brain activity in the healthy brain via the application or induction of an electric current, brain stimulation offers the possibility of establishing a causal relation between particular brain structures and their

associated functions in healthy individuals (Hallett, 2007). Brain stimulation is controlled by the experimenter, and therefore it can be applied at a consistent location across participants, and performance can be measured before, during, and after stimulation. Transcranial magnetic stimulation (TMS) is one stimulation method that has been used to confirm that parietal regions play a critical role in attentional selection and orienting. Hilgetag, Theoret, and Pascual-Leone (2001) used repetitive TMS to induce temporary 'virtual lesions' in parietal cortex of healthy volunteers, and showed that disruption to this region significantly impaired performance on an attention task. Chambers, Payne, Stokes, and Mattingley (2004) used single-pulse TMS to further show that a specific portion of the parietal lobe, the angular gyrus, was critically necessary for attention tasks at two distinct time ranges: at an early stage to support the disengagement of attention from an invalidly cued location and at a later stage to support discriminating the target stimulus at the newly attended location. More recently, Taylor, Muggleton, Kalla, Walsh, and Eimer (2011) combined TMS with electroencephalography (EEG), and provided further

support that the angular gyrus is critically involved in the reorienting of attention.

Whereas patient and TMS studies have provided strong evidence for the brain regions involved in attention mechanisms, EEG and magnetoencephalography (MEG) have provided complimentary evidence for the *temporal structure* of neural activity that is evoked during attention tasks. EEG and MEG reveal cortical oscillations that result from synchronous, periodic activation of large groups of neurons. In the literature, these cortical rhythms are typically subdivided into a few major frequency ranges, each of which has been associated with different functional roles. Most common among these frequency bands are the delta (1–4 Hz), theta (4–8 Hz), alpha (8–14 Hz), beta (14–30 Hz), and gamma (>30 Hz) bands. As described below, oscillations in the alpha and gamma bands, in particular, have been implicated in various aspects of attention.

Alpha oscillations have been a subject of study for roughly 80 years (Jasper & Cruikshank, 1937), but a description of the relationship between attention and alpha activity has emerged only relatively recently. Worden, Foxe, Wang, and Simpson (2000) found that alpha power may be distributed over occipital cortex in a manner that reflects the current locus of visual attention, with *increased* alpha contralateral to the *to-be-ignored* visual hemifield. Thus, increased alpha activity may be related to suppressing perceptual processing of unattended locations in a topographic manner (see also Klimesch, Sauseng, & Gerloff, 2003; Sauseng et al., 2005). Thut, Nietzel, Brandt, and Pascual-Leone (2006) found that a relative *decrease* of alpha power in the hemisphere contralateral to the upcoming *target* predicted improved performance. More recently, Rihs, Michel, and Thut (2009) reported a relative imbalance of alpha power during different *stages* of the attention task, with the initial *orienting* of attention being associated with a relative decrease in alpha power in the contralateral hemisphere, and a later *sustaining* of attention driven by a prolonged increase in the ipsilateral hemisphere.

Gamma band oscillations (>30 Hz) have also been implicated in various functions of attention. Some of the earliest research suggested that gamma synchronization might relate to the so-called binding problem that attention is purported to solve, as features of a given object are bound together by the

synchronous oscillation of the neural populations that underlie those features (Gray & Singer, 1989). More recently, Gruber, Müller, Keil, and Elbert (1999) investigated the orienting of spatial attention and found that the distribution of gamma power following an attention-directing cue was maximal over parieto-occipital sites. The range of frequencies included within the gamma band is quite large, however, and Vidal, Chaumon, O'Regan, and Tallon-Baudry (2006) found evidence that visual grouping and selectively attending are associated with distinct sub-ranges within this band. Specifically, high gamma (70–120 Hz) over central occipital regions was associated with visual grouping, whereas low gamma (44–66 Hz) at right parietal sensors was associated with the focusing of attention. Recent evidence suggests that gamma activity may be involved specifically in the voluntary *disengagement* and *reorienting* of attention. In an EEG study, Landau, Esterman, Robertson, Bentin, and Prinzmetal (2007) found a robust peak of low gamma activity (30–70 Hz) when voluntary reorienting of attention would be required, specifically, following a target that appeared in an unexpected (invalid) location in the endogenous condition. This burst of low gamma activity was not observed for validly cued targets in the endogenous condition, when a reorienting of attention would *not* be required because attention would have already been voluntarily shifted to that location in response to the preceding cue. Indeed, this burst of gamma activity was also observed in response to the endogenous, attention-directing *cue*. Critically, however the *exogenous cue* did not trigger this burst of gamma activity. These results are in line with behavioral (Berger et al., 2005; Jonides, 1981), ERP (Hopfinger & West, 2006), and TMS (Chica, Bartolomeo, & Valero-Cabre, 2011) evidence suggesting that voluntary (i.e., endogenous) and involuntary (i.e., exogenous) attention represent at least partially separate attention systems with somewhat different time courses and effects on behavior and neural activity.

While these EEG and MEG studies have provided insight into the links between neural activity and behavior, the evidence obtained using these methods is ultimately only correlational. Demonstrating causality would require directly influencing a given brain region and then observing the behavioral consequences. In addition to TMS, a group of stimulation techniques

have been developed in which electrical current is passed through the cortex via scalp electrodes. Transcranial direct current stimulation (tDCS) involves delivering direct current (i.e., current of a constant intensity and direction), whereas transcranial alternating current stimulation (tACS) employs a sine-wave stimulation function (Antal & Paulus, 2013; Fröhlich, 2014; Herrmann, Rach, Neuling, & Strüber, 2013) and is thought to engage cortical oscillations in a frequency-specific way (Fröhlich, 2015). Thus, tACS holds potential for determining causality in the correlational associations that have been demonstrated in previous studies of oscillatory network dynamics with EEG and MEG. The aim of the current study was to stimulate inferior parietal cortex of the right hemisphere, using tACS to modulate neural oscillations in the alpha and gamma bands, and observe the consequences of these modulations on exogenous versus endogenous attention.

Methods

Participants

Twenty-three healthy young adults (ages 18–27; 14 female) participated in all conditions and were included in the analyses. Participants were all right handed with 20–20 or corrected to 20–20 vision and no history of psychiatric illness, neurological disorder or incident (such as concussion). The original sample contained 28 participants, but five subjects were excluded because it was unclear if they understood and followed the instructions; their behavioral results in the no-stimulation ('sham') condition showed an inverted validity effect in the endogenous condition, with faster and more accurate responses at the to-be-ignored location. Since the purpose of this experiment was to investigate how neural stimulation may modulate the standard attention cuing effect (i.e., improved performance at the attended location versus the to-be-ignored location in the endogenous condition), we excluded subjects who showed the opposite pattern in the baseline (i.e., sham/no-stimulation) condition.

Procedure

A within-subject experimental design was used. There were three stimulation conditions and during each type of stimulation, participants completed two spatial

cueing tasks—one to assess endogenous attention and one to assess exogenous attention. Experimental sessions were conducted in an electrically-shielded, sound-attenuated booth, and stimuli were presented on a cathode ray tube (CRT) monitor positioned 75 cm from the participant, using Presentation software (v.18.1; www.neurobs.com). The trial sequence for the exogenous task is shown in Figure 1 (left column). Trials began with 500 ms of the background fixation screen, which consisted of a white central fixation cross (subtending 0.61° of visual angle horizontally and vertically), flanked by outline boxes in the left and right visual field (each outline box was a square, 3.36° in each dimension). The fixation cross and outline boxes were present throughout the entire experiment on a gray background. In the exogenous cue condition, a nonpredictive peripheral cue (four dots centered on the outer edges of one box) appeared for 34 ms, followed by an interstimulus interval (ISI) of either 116 ms or 266 ms (the two ISIs were equally likely and were used in order to reduce precise timing expectancies). The target screen was then presented for 50 ms and consisted of a circle (2° of visual angle in diameter) with a gap in the bottom appearing within one of the two peripheral placeholder boxes. The task was to indicate whether the gap was 'large' or 'small' as quickly as possible. The small gap was always one-eighths of the circle, and the large gap could be two-eighths or three-eighths of the circle. Participants responded on a commercial gamepad (Saitek dual analog model FPS P990), pressing one button with their right index finger for a large gap and another button with their right middle finger for a small gap. The location of the target circle was equally likely at the left or right visual field locations. There was a 1000 ms intertrial interval between the response and the start of the next trial. The endogenous trial sequence (Figure 1, right column) was much like the exogenous task, with the following exceptions: (1) an arrow appeared above fixation for 1500 ms before the start of each block of 20 trials indicating which location to attend for that block of 20 trials; (2) there was no peripheral cue; and (3) targets appeared at the location indicated by the arrow (i.e., 'valid' trials) on 80% of trials and at the opposite location ('invalid' trials) on the other 20% of trials.

Before experimental sessions, participants received, at a minimum, two practice blocks: one for each task (exogenous and endogenous). If the participant's accuracy on the practice block for either condition was less

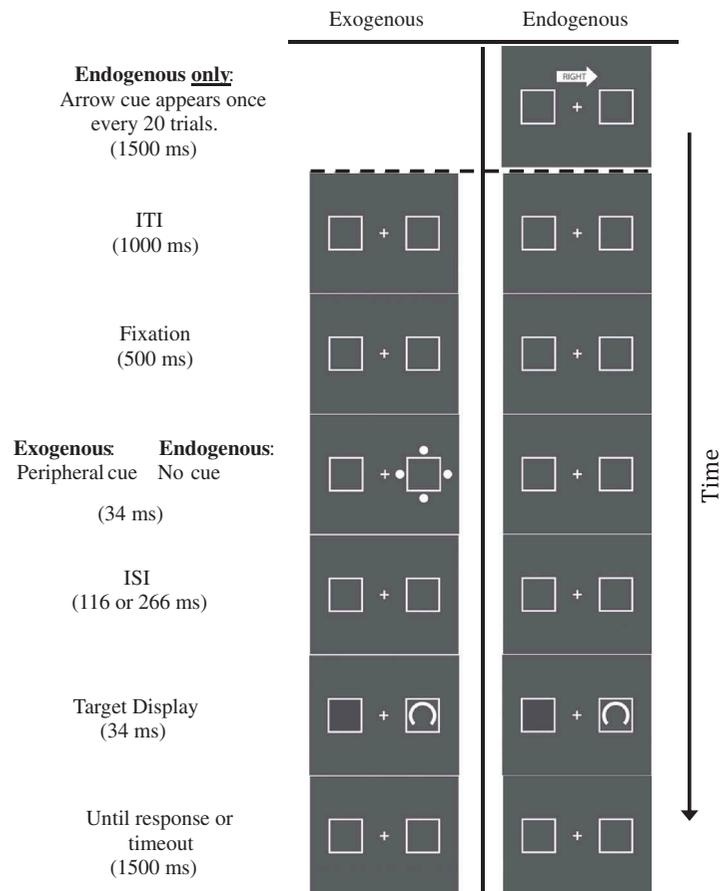


Figure 1. Example trial sequences. The exogenous attention task is shown in the left column; the endogenous attention task is shown in the right column. Note that the stimuli have been enlarged for ease of viewing here.

than 75%, the gap in the large gap stimulus was increased from two-eighths to three-eighths of the circle. The practice block for that condition was then repeated to ensure that the participant was able to perform at an acceptable level before beginning the experiment proper. After practice, the experiment consisted of six blocks: one endogenous and one exogenous for each stimulation condition. Across subjects, the order of the stimulation conditions was counterbalanced. Each block of the endogenous task consisted of 80 trials (to permit 16 invalid trials, along with 64 valid trials); blocks of the exogenous task consisted of 64 trials (32 cued location target trials, 32 uncued location target trials).

Stimulation

There were three stimulation conditions: alpha, gamma, and sham. In previous rTMS and tACS studies, 10 Hz is the most commonly used frequency to engage alpha oscillations (Brignani, Ruzzoli, Mauri, &

Miniussi, 2013; Kanai, Chaieb, Antal, Walsh, & Paulus, 2008; Romei, Gross, & Thut, 2010), and it has been shown to selectively enhance alpha oscillations (Helfrich et al., 2014). Thus, 10 Hz was used in the present study for the alpha stimulation condition. The choice of frequency for gamma is more difficult, considering that the band is in fact very wide (>30 Hz, no agreement on upper cutoff frequency) and attention has been associated with oscillatory activity in a number of sub-bands within this range. However, those studies that looked specifically at focused attention (Doesburg, Roggeveen, Kitajo, & Ward, 2008; Gruber et al., 1999; Vidal et al., 2006) found that synchrony was most prominent in the lower part of the gamma range, around 40 Hz. Therefore, we used 40 Hz in the gamma stimulation condition in the current study, since we were interested specifically in selective attention processes. In both of the active stimulation conditions (10 Hz and 40 Hz), the stimulation was started 45 s before the block of trials and was applied continuously

throughout the entire block of trials. A sham (no-stimulation) condition was also used to ensure any observed changes in performance were not simply due to subjects' expectations of what may happen following stimulation. Active sham conditions are important in tACS studies (Brignani et al., 2013; Laczó, Antal, Niebergall, Treue, & Paulus, 2012) and involve turning on stimulation for a brief period (no more than 30 s) before gradually ramping the intensity down to zero. This ramping on of stimulation allows for the mild tingling sensation that some participants may feel at the initial onset of stimulation (Kanai et al., 2008); this gives the participant the impression that this condition is like the other conditions, thus blinding them to the presence or absence of stimulation. Critically, this brief ramping up of stimulation in the sham condition is brief enough to not have a lasting effect on neural activity. In the sham condition of this experiment, we used 30 s of stimulation at 25 Hz; this stimulation ended before any trials began, and there was no stimulation during the duration of all trials in the sham condition. The 25-Hz frequency was chosen to be midway between the two active stimulation conditions (10 Hz and 40 Hz) to ensure that no one frequency was more frequent in the experiment.

Stimulation was delivered using the NeuroConn DC-Stimulator Plus. Electrode pads were affixed to the scalp using Ten20 conductive paste. The smaller (5×5 cm) stimulating electrode was placed over location 'P6' of the 10–20 standard system for electrode placement (with the cable leading out from the posterior edge) targeting the angular gyrus in the inferior parietal lobe in the right hemisphere (Herwig, Satrapi, & Schönfeldt-Lecuona, 2003). The larger (5×7 cm) stimulation electrode was placed over 'Cz' of the 10–20 standard system (with the cable leading out from the posterior edge) at the intersection of sagittal and coronal midlines. In all three stimulation conditions, the current had a maximum amplitude of 1 mA (2 mA peak-to-peak). In the sham condition, 25-Hz stimulation was applied for only the first 30 s; more specifically, stimulation was ramped up over the first 4 s, stayed on for 22 s, and then was ramped down to zero over the subsequent 4 s. In all cases, the task was started at least 45 s after the beginning of stimulation so that the sham condition would have no ongoing stimulation effects during the task. In contrast to some previous studies that have used 2-mA stimulation, no participants in the present study

reported observing phosphenes. This difference is likely due to previous studies having more frontally located stimulation that could have affected the optic nerve, whereas the present stimulation was located at a lateral posterior location away from the optic nerve and away from primary visual areas.

Results

Manual reaction times for correct trials were first submitted to a $2 \times 3 \times 2 \times 2$ analysis of variance (ANOVA), with factors of attention condition (endogenous, exogenous), stimulation (alpha, gamma, sham), visual field of target (left, right), and validity (valid, invalid). All results here are reported with Greenhouse–Geisser correction for non-sphericity, where applicable. The omnibus analysis resulted in significant main effects of attention condition ($F(1,22) = 7.67, p = .011$) and validity ($F(1,22) = 20.78, p < .001$). The main effect of visual field did not approach significance ($F(1,22) = 0.05, p = .827$), and the main effect of stimulation condition was not significant ($F(1.62,35.65) = 2.04, p = .142$). Critically, however, there was a significant three-way interaction between attention condition, stimulation condition, and validity ($F(1.67,36.83) = 3.53, p = .047$). The only other significant interaction was between attention condition and validity ($F(1,22) = 5.17, p = .033$). To further analyze the three-way interaction, we performed separate analyses for each of the stimulation conditions versus the sham condition (note, these following analyses would be most comparable to previous stimulation studies that only used one stimulation frequency along with sham stimulation).

In the analysis of just the 40 Hz (gamma) stimulation versus sham, the $2 \times 2 \times 2 \times 2$ ANOVA consisted of the factors attention condition (endogenous, exogenous), stimulation (gamma, sham), visual field of target (left, right), and validity (valid, invalid). This analysis revealed significant main effects of attention condition ($F(1,22) = 8.38, p = .008$), validity ($F(1,22) = 10.60, p = .004$), and stimulation ($F(1,22) = 4.40, p = .047$). The main effect of visual field again did not approach significance ($F(1,22) = 0.02, p = .888$). Again, however, there was a significant three-way interaction between attention condition, stimulation condition, and validity ($F(1,22) = 5.14, p = .034$). There were no other significant main effects or interactions, although the two-

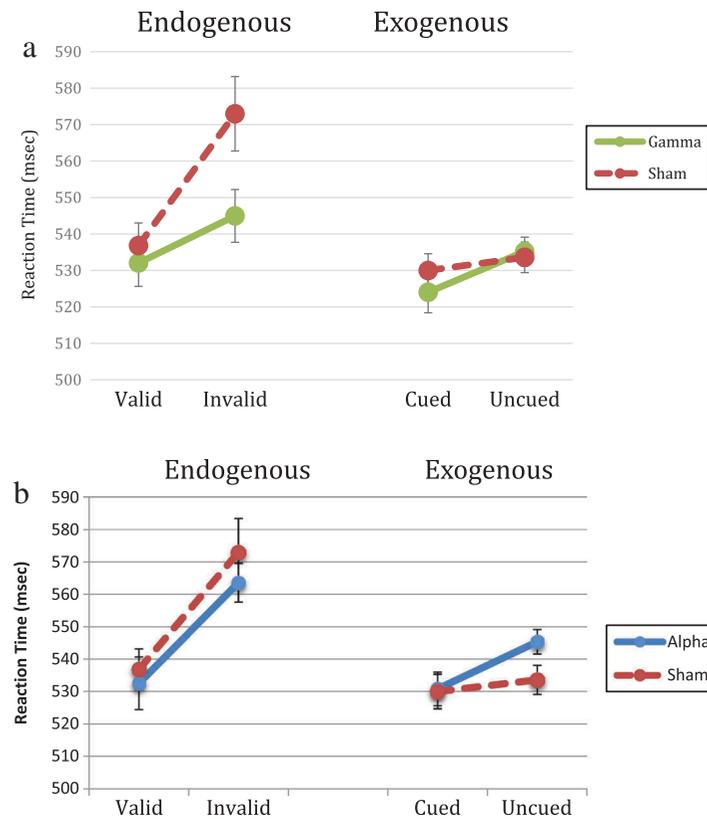


Figure 2. Reaction time results from gamma stimulation (Figure 2(a)) and alpha stimulation (Figure 2(b)) relative to sham (no-stimulation) condition. Valid and invalid refer to the endogenous cuing condition; cued and uncued refer to the exogenous cuing condition. Error bars represent within-subject standard errors of the mean, adjusted using the method of Morey (2008).

way interaction of attention condition by validity was near significant ($F(1,22) = 4.26, p = .051$). As illustrated in Figure 2(a), the three-way interaction was driven predominantly by the effect of gamma stimulation on invalid trials in the endogenous condition. Paired t -tests confirm this, as the only significant difference was that the responses to invalid trials in the endogenous condition were faster in the gamma stimulation condition, relative to that same type of trial in the sham condition ($t(1,22) = -2.179, p = .040$).

In the analysis of just the 10-Hz (Alpha) stimulation versus sham, the $2 \times 2 \times 2 \times 2$ ANOVA consisted of the factors attention condition (endogenous, exogenous), stimulation (10 Hz, sham), visual field of target (left, right), and validity (valid, invalid). This analysis revealed significant main effects of attention condition ($F(1,22) = 5.97, p = .023$) and validity ($F(1,22) = 19.65, p < .001$). The main effects of stimulation ($F(1,22) = 0.004, p = .95$) and visual field did not approach significance ($F(1,22) = 0.001, p = .98$). There was a significant attention condition by

validity interaction ($F(1,22) = 6.99, p = .015$), and interestingly, there was a marginal three-way interaction between attention condition, stimulation condition, and validity ($F(1,22) = 3.23, p = .086$). There were no other significant main effects or interactions. As illustrated in Figure 2(b), the marginal three-way interaction was driven predominantly by the effect of alpha stimulation on invalid/uncued trials in the exogenous condition. Paired t -tests confirm this, as the only difference approaching significance was that the responses to invalid trials in the endogenous condition were significantly slower in the alpha stimulation condition, relative to that same type of trial in the sham condition ($t(1,22) = 1.87, p = .074$). Although any interpretation of these marginal effects must proceed with caution, it is potentially interesting that the only effect approaching significance following alpha stimulation was in the uncued location target trials in the exogenous attention condition, whereas the only significant effect of gamma stimulation was for the *invalid* trials in the endogenous attention condition.

Analyses of the accuracy of responses was also performed, using the same omnibus ANOVA as described above, a $2 \times 3 \times 2 \times 2$ ANOVA, with factors of attention condition (endogenous, exogenous), stimulation (alpha, gamma, sham), visual field of target (left, right), and validity (valid, invalid). This analysis revealed no significant main effects (attention condition: $F(1,22) = 2.124, p = .159$; validity: $F(1,22) = 0.006, p = .939$; visual field: $F(1,22) = 0.622, p = .439$; stimulation condition: $F(2,44) = 1.098, p = .335$). There were also no significant interactions (all p values $>.08$), as accuracy was consistently high across all conditions (mean percent correct = 94.1%; range across conditions = 91.9–96.5%). The critical three-way interaction between attention, stimulation, and validity did not approach significance ($F(1.65,36.26) = 0.864, p = .411$). Therefore, there was no evidence for a speed–accuracy tradeoff that may have affected the reaction time results.

Discussion

Previous studies have shown that the parietal lobe is an important part of the circuitry supporting healthy attention-related functioning (Corbetta & Shulman, 2002; Hopfinger, Buonocore, & Mangun, 2000). The critical role of the parietal lobe, especially in the right hemisphere, has been supported by studies of patients with unilateral neglect (Heilman & Van Den Abell, 1980) and more recently by TMS studies in healthy adults (Chica et al., 2011; Hilgetag et al., 2001). In addition to these studies showing that an intact and functioning inferior parietal lobe is necessary for attention, EEG and MEG studies have provided evidence that the gamma and alpha frequency bands may be associated with different mechanisms of attention (Rihs et al., 2009; Vidal et al., 2006). Here, we were able to use tACS to test whether stimulating the inferior parietal region at frequencies associated with gamma and alpha oscillations affects processes of attention, especially the disengagement of attention from a previously cued location.

The results from the gamma stimulation conditions provide new evidence for the critical role of this oscillation in visual attention. Our results support the view that the right parietal lobe is involved in a disengage mechanism, whereby attention is first disengaged from its present focus before being oriented elsewhere. Our results suggest that this

critical disengage/reorient mechanism is supported by gamma band activity in the parietal lobe. This 40-Hz stimulation did not significantly affect exogenous orienting, and for endogenous orienting, the effect of stimulation was a relative speeding of responses to invalidly cued targets, without affecting validly cued targets. This is in line with the results of Landau et al. (2007), who showed that scalp recorded gamma activity was enhanced specifically when subjects had to reorient attention following an endogenous cue. More work needs to be done with magnetic resonance imaging (MRI)-based targeting and high-definition tACS (Helfrich et al., 2014) to allow a better understanding of the precise portion(s) of the parietal lobe responsible for these effects, but the present findings provide new evidence for the role of gamma oscillations in the reorienting of voluntary attention. We do not yet know if these effects are unique to stimulation over the right parietal lobe, as no other locations were stimulated in the present experiment. Furthermore, although we only found a significant effect of 40-Hz stimulation in the voluntary attention condition, we cannot rule out the possibility that this stimulation could have a similar effect on exogenous attention. In addition to the usual caveats regarding null results, even greater caution needs to be used when interpreting the lack of an effect of exogenous attention in the current results because the standard exogenous cuing effect was not observed in the sham condition. Thus, it is possible that 40-Hz stimulation may affect exogenous orienting, if tested in a paradigm that more strongly triggers attentional capture. The present results do, however, provide new evidence that 40-Hz stimulation does affect the disengagement and reorienting of voluntary attention.

The effects from our 10-Hz (alpha) stimulation condition are not as robust, but we briefly discuss the interesting trends. The 10-Hz stimulation had essentially no effect, relative to sham stimulation, in the endogenous condition. This was somewhat surprising, given that a number of previous studies have suggested an important role for alpha oscillations in attention. However, many of those studies report alpha over occipital areas (Thut et al., 2006; Worden et al., 2000), not the parietal regions we stimulated here. In the exogenous condition of the present study, however, we do find a trend for alpha stimulation to affect the pattern of reaction times. Our 10-Hz

stimulation appears to enhance the cuing effect (relative to sham) following an exogenous cue, mainly through slowing down the responses to invalid trials. It should be noted, however, that the exogenous cue in this experiment did not robustly capture attention in the sham condition, as cued location targets and uncued location targets were responded to almost equally quickly. Therefore, it may be that the present cue was relatively subtle, and the target was robust enough that reaction times in the sham condition were essentially at floor. This may provide some insight into the effect of 10-Hz stimulation. EEG studies have shown that alpha activity is increased over regions of occipital cortex representing to-be-ignored locations, and stimulation studies have provided evidence that increasing alpha activity over visual processing regions can sometimes impair visual perception. Thus, it may be that in the present study, stimulating alpha in the parietal lobe increases alpha within bilateral visual cortices, decreasing the overall perceptibility of the target stimuli, and thus allowing the exogenous cue to have a stronger effect. Furthermore, our results suggest that within this stimulation-induced perceptually noisier environment, there may be a stronger *holding of attention* by the exogenous cue, thereby slowing the disengagement of attention. Previously, we have used other paradigms to investigate the automatic *holding of attention* (Parks, Kim, & Hopfinger, 2014) and it may be informative to use tACS in those paradigms to see if the holding of attention in a nonspatial attention task is also modulated by stimulating inferior parietal regions at alpha band frequencies.

In summary, the present results provide new evidence that oscillatory stimulation at specific frequencies modulates the mechanisms of attention in a visual discrimination task. Critically, the present results lend further support to theories that have suggested that exogenous and endogenous attention are indeed two separate types of attention (Chica et al., 2011; Hopfinger & West, 2006; Landau et al., 2007). This distinction may be important for tailoring therapies and treatments to better target the brain regions, and the specific neural activity patterns, that underlie each type of attention. The present finding that attention can be modulated using tACS may ultimately have clinical applications as well. Indeed, several studies have already

demonstrated beneficial effects of tACS in a variety of domains, including creativity (Lustenberger, Boyle, Foulser, Mellin, & Fröhlich, 2015), motor learning (Pollok, Boysen, & Krause, 2015), musical ability (Schaal, Pfeifer, Krause, & Pollok, 2015), and fluid intelligence (Santarnecchi et al., 2013, 2016). Given that attention underlies so many cognitive and emotional skills, there may be great potential for enhancing a wide variety of abilities (Fröhlich, Sellers, & Cordle, 2015). Moreover, the ability to modulate attention using tACS may open new therapeutic avenues for attention-deficit hyperactivity disorder, for which tDCS therapies are already being pursued (Ditye, Jacobson, Walsh, & Lavidor, 2012; Rubio-Morell et al., 2011).

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Disclosure statement

No potential conflict of interest was reported by the authors.

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