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The Influence of Posterior Parietal Cortex on Extrastriate Visual Activity: A Concurrent TMS and Fast Optical Imaging Study

Nathan A. Parks[1], **Chiara Mazzi**[2], **Evelina Tapia**[3,4], **Silvia Savazzi**[2], **Monica Fabiani**[3,4], **Gabriele Gratton**[3,4], and **Diane M. Beck**[3,4]

[1]University of Arkansas

[2]University of Verona

[3]University of Illinois, Urbana-Champaign

[4]Beckman Institute for Advanced Science and Technology

Abstract

The posterior parietal cortex (PPC) is a critical node in attentional and saccadic eye movement networks of the cerebral cortex, exerting top-down control over activity in visual cortex. Here, we sought to further elucidate the properties of PPC feedback by providing a time-resolved map of functional connectivity between parietal and occipital cortex using single-pulse TMS to stimulate the left PPC while concurrently recording fast optical imaging data from bilateral occipital cortex. Magnetic stimulation of the PPC induced transient ipsilateral occipital activations (BA 18) 24 to 48 ms post-TMS. Concurrent TMS and fast optical imaging results demonstrate a clear influence of PPC stimulation on activity within human extrastriate visual cortex and further extend this time- and space-resolved method for examining functional connectivity.

Keywords

brain connectivity; transcranial magnetic stimulation (TMS); near-infrared optical imaging; event-related optical signal (EROS); posterior parietal cortex; phosphene

Introduction

Feedback projections from posterior parietal cortex (PPC) into more posterior visual areas provide top-down modulation of visual activity, and these signals are proposed to be essential to functions of the attentional and eye-movement systems of the human cerebral cortex (Beck & Kastner, 2009; Behrmann, Geng, & Shomstein, 2004; Colby & Goldberg, 1999; Corbetta & Shulman, 2002; Desimone & Duncan, 1995). Functional magnetic resonance imaging (fMRI) studies have shown strong correlations between PPC activity and

Please address correspondence to: Nathan Parks, Department of Psychological Science, University of Arkansas, 216 Memorial Hall, Fayetteville, AR 72701, naparks@uark.edu, Phone: 479-575-5813, Fax: 479-575-3219.

activity within visual cortices in selective attention and oculomotor planning tasks (Bressler, Tang, Sylvester, Shulman, & Corbetta, 2008; Lauritzen, D'Esposito, Heeger, & Silver, 2009; Merriam, Genovese, & Colby, 2003, 2007; Silver, Ress, & Heeger, 2005; Yantis et al., 2002). Disruption of the PPC with transcranial magnetic stimulation (TMS) has been shown to impair oculomotor planning (Muri, Vermersch, Rivaud, & Gaymard, 1996; Zangemeister, Canavan, & Hoemberg, 1995) and visual attention (Beck, Muggleton, Walsh, & Lavie, 2006; Chambers, Payne, Stokes, & Mattingley, 2004; Hilgetag, Théoret, & Pascual-Leone, 2001; Thut, Nietzel, & Pascual-Leone, 2005). TMS studies have further shown that phosphene thresholds measured from visual cortex decrease directly following TMS to PPC stimulation, demonstrating a direct influence of PPC stimulation on the excitability of visual cortex (Silvanto et al., 2009). Recent advances in the concurrent application of TMS and neuroimaging (Bestmann et al., 2008; Driver, Blankenburg, Bestmann, Vanduffel, & Ruff, 2009; Miniussi & Thut, 2010; Siebner et al., 2009; Taylor & Thut, 2012) have provided more detailed neurophysiological measures of PPC stimulation on remote visual areas by using TMS to stimulate PPC while concurrently recording activity from visual cortex using fMRI (Blankenburg et al., 2010; Ruff et al., 2008, 2009) or event-related potentials (ERP; Fuggetta et al., 2006). However, unlike the frontal eye fields (FEF, another player in the attention and eye-movement network), the precise temporal and spatial characteristics of the PPC's influence on occipital cortex has yet to be described (Moore & Armstrong, 2003; Armstrong, Fitzgerald & Moore, 2006; Armstrong & Moore, 2007).

Recent work has demonstrated that fast near-infrared optical imaging can also be effectively used concurrently with TMS to measure inter-regional TMS-evoked cortical activations (Parks et al., 2012; Parks, 2013). Fast optical imaging (also called the event-related optical signal, or EROS) has high spatial and temporal resolution as it is based on the modeled diffusion paths of near-infrared light and changes in the scattering of this light as it passes through depolarized neural tissue (phase or photon delay data; Gratton, Corballis, Cho, Fabiani, & Hood, 1995; Gratton et al., 1997; Gratton & Fabiani, 2003; Gratton, Goodman-Wood, & Fabiani, 2001; Gratton et al., 2006; for reviews see Gratton & Fabiani, 2010; Wolf et al., 2008). When combined with TMS, fast optical imaging affords a unique opportunity to interrogate the effects of PPC stimulation on visual cortex activity with sub-centimeter spatial resolution and millisecond temporal resolution. Thus, unlike fMRI or ERP, which have limitations in resolving neural signals in time (fMRI) or space (ERP), fast optical imaging allows for the spatiotemporal dynamics of TMS-evoked inter-regional activations to be mapped.

Here, we conducted a simultaneous TMS and fast optical imaging experiment to measure interregional cortical activations evoked in the human cerebral cortex during PPC stimulation. We performed this experiment with two goals in mind. First, we sought to investigate the influence of PPC stimulation on occipital visual areas, including the time-course of these TMS-induced activations. To this end we recorded fast optical imaging from bilateral occipital cortex while single pulses of TMS were administered to the left PPC. We used event-related fast optical signals time-locked to TMS onset to image the spatiotemporal dynamics of PPC feedback in occipital visual cortex. The second goal of our study was to further demonstrate the utility of concurrent TMS and fast optical imaging in providing time- and space-resolved measurement of TMS-evoked inter-regional activations. The

method has been previously applied only in the motor system (Parks et al., 2012). Here, we extend the method to demonstrate measures of functional connectivity in the human visual system.

Method

Subjects

Ten right-handed subjects were recruited from the University of Illinois graduate and undergraduate population. Prior to their participation, subjects were screened for safety with TMS according to the guidelines described by Rossi and colleagues (2009). In order to ensure that parietal stimulation was sufficient to influence the brain we used the presence of TMS-induced phosphenes; if TMS resulted in a visual percept we could be sure that it was impacting cortical activity. Previous work has established that, like occipital TMS, a phosphene percept can be also induced with TMS to parietal cortex (Bagattini, Mazzi, & Savazzi, 2015; Fried, ElkinFrankston, Rushmore, Hilgetag, & Valero-Cabre, 2011; Marzi, Mancini, & Savazzi, 2009; Mazzi, Mancini, & Savazzi, 2014; Tapia, Mazzi, Savazzi, & Beck, 2014). Thus, subjects were pre-screened for reliability of parietal phosphene percept. Subjects participating in this experiment were drawn from a bank of subjects who had previously participated in laboratory experiments and were pre-screened for parietal phosphenes as part of those projects. The prescreening process assessed the reliability of both occipital and parietal phosphenes by evaluating the consistency of phosphene report under sham and active stimulation conditions. Occipital and parietal thresholds were used to adjust stimulator intensity according to individual subject sensitivity. All TMS, optical imaging, and psychophysical procedures were approved by the University of Illinois Institutional Review Board.

Stimuli and Procedures

Experimentation was conducted in a dark room. Stimuli were displayed using the Presentation® stimulus delivery package (Neurobehavioral Systems, Albany, CA, USA) on a 19-inch CRT monitor. Scalp locations for TMS were measured and marked with a grease pencil. Then, following a 10 to 15 minute period of dark adaptation, TMS was positioned over the P3 scalp location of the international 10-20 system (Jasper, 1958). P3 overlays left PPC with variation of less than 2 cm (Herwig et al., 2003), a margin of error which would be expected to be further minimized across subjects by the width of the figure-of-eight coil's magnetic field (∼2 cm). Parietal phosphene threshold was determined at P3 and the near-infrared optical imaging apparatus of source and detector fibers was then affixed to the subject's head. Subjects were dark-adapted once again for a 10 to 15 minute period before testing began.

Optical imaging data were recorded while single-pulses of TMS were administered to the left PPC (position P3 of the 10-20 system) or a control site several centimeters away. A control site was determined individually for each subject so as to provide sufficient separation from the P3 stimulation site while also ensuring that muscle-twitch artifacts were not introduced at the control location (see *Transcranial Magnetic Stimulation*). Subjects were positioned at a distance of 57 cm from the screen. Their head position was stabilized

using a chin rest with forehead support. Foam padding further secured the head in position and minimized head movements during testing. Subjects were instructed to maintain a steady fixation on a faint red dot centered on the screen with a 32° × 27° field of view. Trials began with a random fixation interval of 1500 – 2500 ms. A single pulse of TMS was then administered and a dim gray question mark appeared over the fixation point after a 500 ms delay (Figure 1). Subjects then responded with a button press to indicate whether or not they had perceived a phosphene by pressing '1' or '2' on the keyboard number pad, respectively. Five blocks of 50 trials were given for both P3 and control TMS conditions. TMS coil position was alternated between blocks (P3 or control site TMS).

Following experimentation, three-dimensional coordinates of the scalp locations of the optical sensors (optodes) were digitized for each subject, using the Brainsight® software package (Rogue Research, Montreal, Canada) equipped with a Polaris Vicra® optical tracking system (NDI, Waterloo, Ontario, Canada). Three fiducial points (nasion, left and right pre-auricular points) and an additional 50 positions from the scalp and face were also digitized to fully capture head shape.

Transcranial Magnetic Stimulation

TMS was administered using a Magstim 220® stimulator (Magstim, Whitland, UK) outfitted with a 70 mm figure-of-eight coil. Single TMS pulses were administered to one of two locations over the left hemisphere in an anterior-to-posterior orientation. Position P3 was used as the active site for posterior parietal stimulation. Stimulation over this scalp location corresponds to BA 7/39/40 (Herwig et al. 2003; Okamoto et al., 2004). We verified that coil position induced suprathreshold stimulation of PPC by ensuring that TMS to this location elicited a phosphene percept (Bagattini et al., 2015; Fried et al., 2011; Marzi et al., 2009; Mazzi et al., 2014; Tapia et al., 2014). We selected a stimulation site that elicited parietal phosphenes so that stimulation intensity could be set according to this phosphene threshold to ensure suprathreshold stimulation of PPC. A control site was selected individually for each subject at a location over the left hemisphere that was approximately 3 cm anterior and dorsal to P3 and did not evoke muscle twitches of the face, scalp, neck, or extremities. To set stimulator intensity individual for each subject, a 50% phosphene threshold was measured at P3 using the rapid estimation of phosphene thresholds (REPT) method (Abrahamayan et al., 2011). Stimulator intensity was then set to 120% of this threshold value for the duration of the experiment. TMS coil positioning was guided by a Brainsight® neuronavigation system (Rogue Research Inc., Montreal, Quebec, Canada), ensuring accurate coil placement between stimulation runs.

Fast Optical Imaging

Optical recordings were taken using Imagent® frequency-domain oxymeters (ISS, Champaign, IL). Fiber optic near-infrared (NIR) sources and detectors were secured to parietal and occipital regions using a custom built mounting apparatus (Figure 2). The optical recording montage consisted of 16 detectors and 12 source fibers mounted to the scalp over right parietal, left occipital, and right occipital regions. The optical recording apparatus was mounted with respect to P3 and control site locations, leaving enough separation to ensure the unimpeded administration of TMS pulses. Source fibers emitted

NIR light at 830 nm, amplitude-modulated at 110 MHz. Phase delay data were sampled from 80 channels (source-detector pairs) at 8 ms intervals (125 Hz). To achieve a sampling rate of 125 Hz, we designed our optical montage such that a subset of near-infrared sources could be illuminated simultaneously without causing channel crosstalk (i.e., allowing for a large spatial separation across the two hemispheres). This permitted multiplexing through five sources over an 8 ms period (1.6 ms duration of illumination per source).

Pre-processing of continuous fast optical data included correction of phase wrapping, conversion of phase to optical delay, amplitude normalization (within blocks), pulse artifact correction (Gratton & Corballis, 1995), and a low-pass filter of 30 Hz (see Gratton & Fabiani, 2010 for a review of optical analysis). Fast optical signals were then segmented into 600 ms epochs, beginning 192 ms prior to TMS onset (pre-stimulus baseline) and continuing 408 ms thereafter. Separate event-related averages were then formed for P3 and control site TMS blocks. Three-dimensional digitization was used to co-register source and detector fibers to a structural T1-weighted MRI collected from each subject in independent sessions. Co-registration was accomplished using the method described by Whalen et al. (2008) implemented in custom Matlab code (Mathworks, Natick, MA, USA). Co-registration to individual neuroanatomy improves the spatial resolution and signal-to-noise of fast optical signals (Whalen et al., 2008; Gratton & Fabiani, 2010). Modeling of near-infrared diffusion paths and group-level level statistical analyses were conducted with custom analysis software package, OPT-3D (Gratton, 2000). Source-detector pairs (channels) below a distance of 2.5 cm (too short to pass through cortex) or exceeding a distance of 6.0 cm (too far to reliably detect) were excluded from analysis as were channels in which the standard deviation of phase delay in the 600 ms average exceeded 160 ps. Data were baseline-corrected according to the 192 ms pre-stimulus interval, transformed into Talairach space (Talairach & Tournoux, 1988), and spatially smoothed with an 8-mm Gaussian filter. Group-level *T* statistics were calculated at each voxel for a P3 versus control site TMS contrast then converted to *Z* scores. Statistical parametric maps were surface-projected onto a coronal orientation (see posterior view of template Talairach brain; Figure 2). Three 3.0 × 2.5 cm surface-projected regions of interest (ROIs) were examined (X and Z dimensions). These ROIs were selected to encompass occipital visual cortices (Brodmann areas 17 and 18) in the left and right hemispheres (left hemisphere: x=-31 to x=-1 and z=-30 to z=-5; right hemisphere: x=4 to x=34 and z=-30 to z=-5). A third ROI examined potential interhemispheric propagation to the right PPC. This ROI was centered on the mean cortical projection of 10-20 position P4 in Talairach space (Okamoto et al., 2004; x=22 to x=52 and z=36 to z=61). Correction for multiple comparisons within each ROI was calculated based on the number of independent ROI resolution elements (resels; Friston et al., 1994; Gratton et al., 2006). ROI peak Z scores achieving statistical significance ($p < .05$) determined significant activity at each time sample.

Results

Analysis of phosphene reports revealed that subjects perceived a greater proportion of phosphenes with P3 stimulation than control site stimulation (P3 TMS: M= 55.7%, SD=19.1%; control site TMS: M=33.5%, SD=34.94%; t(9)=2.61, p=.028), consistent with greater activation of PPC with P3 stimulation than control site stimulation (Bagattini et al.,

2015; Fried et al., 2011; Marzi et al., 2009; Mazzi et al., 2014; Tapia et al., 2014). However, it should be noted that the relatively high rate of phosphene reports associated with control site stimulation may indicate some spread of activation to left PPC during control site TMS.

Fast optical signals revealed significant TMS-evoked activity within the left occipital ROI beginning 24 ms post-TMS (Z=3.03, Z_{crit} = 2.90; peak voxel: -21, -98, -18) and continuing at 32 ms (Z=2.62, Z_{crit} = 2.62; peak voxel: -21, -97, -13) and 40 ms (Z=2.13, Z_{crit} = 2.07; peak voxel: -6, -100, -6). This activation corresponds to BA 18, consistent with activation of visual extrastriate cortex through parietal feedback connections (Figure 3). There were no significant activations in the right occipital ROI (Z<1.5)consistent with the known ipsilateral effects of PPC TMS stimulation, and with the right visual field lateralization of the phosphenes. The time course of TMS-evoked activation for the P3 TMS versus control site TMS contrast is shown for the first 48 ms in Figure 3. Time course plots of raw optical signals from left and right ROIs are given in Figure 4. No significant contralateral (right) PPC activations were found (Z < 1.5).

Discussion

We investigated the spatiotemporal dynamics of feedback from PPC to more posterior occipital visual areas. Imaging of such functional connectivity between PPC and occipital visual cortices was conducted using a concurrent brain stimulation and neuroimaging approach: we stimulated the left PPC with single-pulses of TMS and used simultaneous recordings of near-infrared fast optical imaging to measure the resultant inter-regional propagation of the TMS-induced activity. Fast optical imaging of bilateral occipital cortex and right parietal cortex revealed a transient activation of left occipital cortex (BA 18) 24 to 48 ms following TMS to left PPC, demonstrating a clear effect of PPC simulation on extrastriate visual cortical activity.

Our results align with previous studies examining the causal influence of PPC feedback on posterior visual areas but provide a more complete view of the spatiotemporal dynamics of PPC-to-occipital feedback in the human brain. Previous work using multi-site TMS demonstrated that occipital phosphene thresholds were reduced 50 ms after PPC stimulation, bilaterally following right PPC stimulation and only ipsilaterally following left PPC stimulation (Silvanto et al., 2009). Our fast optical imaging results are consistent with this spatial pattern and time range as we observe activations within left BA18, which onset at 24 ms and continue 48 ms post-pulse. Previous TMS-fMRI studies have also demonstrated activation of extrastriate visual areas when a short train of TMS pulses is applied to PPC in the right hemisphere (Ruff et al., 2008, 2009). Our fast optical imaging results further elaborate on the timing of this interregional PPC-to-occipital activation, demonstrating modulation of occipital visual activity within a few tens of milliseconds. It should be noted, however, that a previous TMS-fMRI study (Ruff et al., 2009) failed to find significant modulation of occipital visual activity when left PPC was stimulated with TMS (Ruff et al., 2009). One potential reason for this discrepancy in left PPC effects is that Ruff et al. (2009) tested subjects under photopic conditions whereas subjects in both Silvanto et al. (2009) and the present study remained dark-adapted throughout experimentation.

In addition to further elucidating the influence of PPC on occipital visual activity, the results of this concurrent TMS and fast optical imaging study further demonstrate the utility of this technique and highlight the unique information that can be garnered by this neuroimaging approach. A previous study first demonstrated the feasibility of this technique by using single-pulse TMS to induce activations within primary motor cortex and measuring the resultant propagation of intra- and inter-regional activity with fast near-infrared optical imaging (Parks et al., 2012). Concurrent TMS and fast optical imaging recordings allow TMS-evoked responses to be imaged with high temporal (< 10 ms) and spatial ($\sim$1 cm^3) resolution. Here, we successfully follow up on this methodology and extend its application to another modality, providing valuable information regarding the timing of inter-regional communication within a parietal-occipital network of the human visual system.

Our fast optical imaging results are consistent with axonal tracing studies in non-human primates (Andersen, Asanuma, Essick, & Siegel, 1990; Cavada & Goldman-Rakic, 1989). However, there are two caveats to our findings that should be noted. First, unlike tracing studies, our data are unable to discriminate the intrinsic anatomical directionality of the functional activations induced in BA 18 by PPC stimulation. TMS-induced activations may propagate inter-regionally via orthodromic stimulation, antidromic stimulation, or both. Thus, the neuroimaging of TMS-evoked activity is, at present, incapable of determining whether inter-regional activations were induced via signal propagation along afferent or efferent fibers. Second, our selection of a control site was proximal enough to P3 that there may still have been some spread of activation to left PPC, which may have impacted the spatial extent and magnitude of activations observed in occipital cortex.

In summary, our concurrent TMS and fast optical imaging findings demonstrate a functional relationship between PPC and extrastriate visual cortices, revealing that stimulation of PPC influences occipital cortical activity within 24 ms of a TMS pulse. These results provide novel information regarding the timing and spatial distribution of PPC-extrastriate functional connectivity and further demonstrate the unique advantages of concurrent TMS and fast optical imaging recordings.

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References

Abrahamyan A, Clifford CW, Ruzzoli M, Phillips D, Arabzadeh E, Harris JA. Accurate and rapid estimation of phosphene thresholds (REPT). PloS one. 2011; 6:e22342. [PubMed: 21799833]

Andersen RA, Asanuma C, Essick G, Siegel RM. Corticocortical connections of anatomically and physiologically defined subdivisions within the inferior parietal lobule. Journal of Comparative Neurology. 1990; 296:65. [PubMed: 2358530]

Bagattini C, Mazzi C, Savazzi S. Waves of awareness for occipital and parietal phosphenes perception. Neuropsychologia. 2015; 70:114–125. [PubMed: 25698639]

Beck DM, Kastner S. Top-down and bottom-up mechanisms in biasing competition in the human brain. Vision Research. 2009; 49:1154–1165. [PubMed: 18694779]

Beck DM, Muggleton N, Walsh V, Lavie N. Right parietal cortex plays a critical role in change blindness. Cerebral Cortex. 2006; 16:712–717. [PubMed: 16120797]

Behrmann M, Geng JJ, Shomstein S. Parietal cortex and attention. Current Opinion in Neurobiology. 2004; 14:212–217. [PubMed: 15082327]

Bestmann S, Ruff CC, Blankenburg F, Weiskopf N, Driver J, Rothwell JC. Mapping causal interregional influences with concurrent TMS–fMRI. Experimental Brain Research. 2008; 191:383–402. [PubMed: 18936922]

Blankenburg F, Ruff CC, Bestmann S, Bjoertomt O, Josephs O, Deichmann R, Driver J. Studying the role of human parietal cortex in visuospatial attention with concurrent TMS–fMRI. Cerebral Cortex. 2010; 20:2702–2711. [PubMed: 20176690]

Bressler SL, Tang W, Sylvester CM, Shulman GL, Corbetta M. Top-down control of human visual cortex by frontal and parietal cortex in anticipatory visual spatial attention. Journal of Neuroscience. 2008; 28:10056–10061. [PubMed: 18829963]

Cavada C, Goldman-Rakic PS. Posterior parietal cortex in rhesus monkey: I. Parcellation of areas based on distinctive limbic and sensory corticocortical connections. Journal of Comparative Neurology. 1989; 287:393–421. [PubMed: 2477405]

Chambers CD, Payne JM, Stokes MG, Mattingley JB. Fast and slow parietal pathways mediate spatial attention. Nature Neuroscience. 2004; 7:217–218. [PubMed: 14983182]

Colby CL, Goldberg ME. Space and attention in parietal cortex. Annual Review of Neuroscience. 1999; 22:319–349.

Corbetta M, Shulman GL. Control of goal-directed and stimulus-driven attention in the brain. Nature Reviews Neuroscience. 2002; 3:201–215. [PubMed: 11994752]

Desimone R, Duncan J. Neural mechanisms of selective visual attention. Annual Review of Neuroscience. 1995; 18:193–222.

Driver J, Blankenburg F, Bestmann S, Vanduffel W, Ruff CC. Concurrent brain-stimulation and neuroimaging for studies of cognition. Trends in Cognitive Sciences. 2009; 13:319–327. [PubMed: 19540793]

Fried PJ, Elkin-Frankston S, Rushmore RJ, Hilgetag CC, Valero-Cabre A. Characterization of visual percepts evoked by noninvasive stimulation of the human posterior parietal cortex. PloS One. 2011; 6:e27204. [PubMed: 22087266]

Friston KJ, Holmes AP, Worsley KJ, Poline JP, Frith CD, Frackowiak RS. Statistical parametric maps in functional imaging: a general linear approach. Human Brain Mapping. 1994; 2:189–210.

Fuggetta G, Pavone EF, Walsh V, Kiss M, Eimer M. Cortico-cortical interactions in spatial attention: a combined ERP/TMS study. Journal of Neurophysiology. 2006; 95:3277–3280. [PubMed: 16436477]

Gratton G. “Opt-cont” and “opt-3D”: A software suite for the analysis and 3D reconstruction of the event-related optical signal (EROS). Psychophysiology. 2000; 37:S44–S44.

Gratton G, Brumback CR, Gordon BA, Pearson MA, Low KA, Fabiani M. Effects of measurement method, wavelength, and source-detector distance on the fast optical signal. Neuroimage. 2006; 32:1576–1590. [PubMed: 16872842]

Gratton G, Corballis PM. Removing the heart from the brain: compensation for the pulse artifact in the photon migration signal. Psychophysiology. 1995; 32:292–299. [PubMed: 7784538]

Gratton G, Corballis PM, Cho E, Fabiani M, Hood DC. Shades of gray matter: Noninvasive optical images of human brain reponses during visual stimulation. Psychophysiology. 1995; 32:505–509. [PubMed: 7568645]

Gratton G, Fabiani M, Corballis PM, Hood DC, Goodman-Wood MR, Hirsch J, et al. Gratton E. Fast and localized event-related optical signals (EROS) in the human occipital cortex: comparisons with the visual evoked potential and fMRI. Neuroimage. 1997; 6:168–180. [PubMed: 9344821]

Gratton G, Fabiani M. Fast optical imaging of human brain function. Frontiers in Human Neuroscience. 2010; 4:52. [PubMed: 20631845]

Gratton G, Fabiani M. The event-related optical signal (EROS) in visual cortex: replicability, consistency, localization, and resolution. Psychophysiology. 2003; 40:561–571. [PubMed: 14570164]

Gratton G, Goodman-Wood MR, Fabiani M. Comparison of neuronal and hemodynamic measures of the brain response to visual stimulation: an optical imaging study. Human Brain Mapping. 2001; 13:13–25. [PubMed: 11284043]

Herwig U, Satrapi P, Schönfeldt-Lecuona C. Using the international 10-20 EEG system for positioning of transcranial magnetic stimulation. Brain Topography. 2003; 16:95–99. [PubMed: 14977202]

Hilgetag CC, Théoret H, Pascual-Leone A. Enhanced visual spatial attention ipsilateral to rTMS-induced 'virtual lesions' of human parietal cortex. Nature Neuroscience. 2001; 4:953–957. [PubMed: 11528429]

Jasper HH. The ten-twenty electrode system of the International Federation. Electroencephalography and Clinical Neurophysiology. 1958; 10:371–375.

Lauritzen TZ, D'Esposito M, Heeger DJ, Silver MA. Top–down flow of visual spatial attention signals from parietal to occipital cortex. Journal of Vision. 2009; 9:18. [PubMed: 20055551]

Marzi CA, Mancini F, Savazzi S. Interhemispheric transfer of phosphenes generated by occipital versus parietal transcranial magnetic stimulation. Experimental Brain Research. 2009; 192:431–441. [PubMed: 18663438]

Mazzi C, Mancini F, Savazzi S. Can IPS reach visual awareness without V1? Evidence from TMS in healthy subjects and hemianopic patients. Neuropsychologia. 2014; 64:134–144. [PubMed: 25258247]

Merriam EP, Genovese CR, Colby CL. Spatial updating in human parietal cortex. Neuron. 2003; 39:361–373. [PubMed: 12873391]

Merriam EP, Genovese CR, Colby CL. Remapping in human visual cortex. Journal of Neurophysiology. 2007; 97:1738. [PubMed: 17093130]

Miniussi C, Thut G. Combining TMS and EEG offers new prospects in cognitive neuroscience. Brain Topography. 2010; 22:249–256. [PubMed: 19241152]

Muri RM, Vermersch AI, Rivaud S, Gaymard B, Pierrot-Deseilligny C. Effects of single-pulse transcranial magnetic stimulation over the prefrontal and posterior parietal cortices during memory-guided saccades in humans. Journal of Neurophysiology. 1996; 76:2102–2106. [PubMed: 8890321]

Okamoto M, Dan H, Sakamoto K, Takeo K, Shimizu K, Kohno S, et al. Three-dimensional probabilistic anatomical cranio-cerebral correlation via the international 10– 20 system oriented for transcranial functional brain mapping. Neuroimage. 2004; 21:99–111. [PubMed: 14741647]

Parks NA. Concurrent application of TMS and near-infrared optical imaging: methodological considerations and potential artifacts. Frontiers in Human Neuroscience. 2013; 7:592. [PubMed: 24065911]

Parks NA, Maclin EL, Low KA, Beck DM, Fabiani M, Gratton G. Examining cortical dynamics and connectivity with simultaneous single-pulse transcranial magnetic stimulation and fast optical imaging. Neuroimage. 2012; 59:2504–2510. [PubMed: 21925608]

Rossi S, Hallett M, Rossini PM, Pascual-Leone A, et al. Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. Clinical Neurophysiology. 2009; 120:2008–2039. [PubMed: 19833552]

Ruff CC, Bestmann S, Blankenburg F, Bjoertomt O, Josephs O, Weiskopf N, et al. Driver J. Distinct causal influences of parietal versus frontal areas on human visual cortex: evidence from concurrent TMS–fMRI. Cerebral Cortex. 2008; 18:817–827. [PubMed: 17652468]

Ruff CC, Blankenburg F, Bjoertomt O, Bestmann S, Weiskopf N, Driver J. Hemispheric differences in frontal and parietal influences on human occipital cortex: Direct confirmation with concurrent TMS–fMRI. Journal of Cognitive Neuroscience. 2009; 21:1146–1161. [PubMed: 18752395]

Rushworth MFS, Taylor PCJ. TMS in the parietal cortex: updating representations for attention and action. Neuropsychologia. 2006; 44:2700–2716. [PubMed: 16455113]

Siebner HR, Bergmann TO, Bestmann S, Massimini M, Johansen-Berg H, Mochizuki H, et al. Rossini PM. Consensus paper: combining transcranial stimulation with neuroimaging. Brain Stimulation. 2009; 2:58–80. [PubMed: 20633405]

Silvanto J, Muggleton N, Lavie N, Walsh V. The perceptual and functional consequences of parietal top-down modulation on the visual cortex. Cerebral Cortex. 2009; 19:327–330. [PubMed: 18515296]

Silver MA, Ress D, Heeger DJ. Topographic maps of visual spatial attention in human parietal cortex. Journal of Neurophysiology. 2005; 94:1358–1371. [PubMed: 15817643]

Talairach, J.; Tournoux, P. A co-planar stereotaxic atlas of a human brain. Theime; Stuttgart: 1988.

Tapia E, Mazzi C, Savazzi S, Beck DM. Phosphene-guided transcranial magnetic stimulation of occipital but not parietal cortex suppresses stimulus visibility. Experimental Brain Research. 2014; 232:1989–1997. [PubMed: 24584900]

Taylor PCJ, Thut G. Brain activity underlying visual perception and attention as inferred from TMS–EEG: A review. Brain Stimulation. 2012; 5:124–129. [PubMed: 22494831]

Thut G, Nietzel A, Pascual-Leone A. Dorsal posterior parietal rTMS affects voluntary orienting of visuospatial attention. Cerebral Cortex. 2005; 15:628–638. [PubMed: 15342434]

Whalen C, Maclin EL, Fabiani M, Gratton G. Validation of a method for coregistering scalp recording locations with 3D structural MR images. Human Brain Mapping. 2008; 29:1288–1301. [PubMed: 17894391]

Wolf M, Morren G, Haensse D, Karen T, Wolf U, Fauchere JC, et al. Near infrared spectroscopy to study the brain: an overview. Opto-Electronics Review. 2008; 16:413–419.

Yantis S, Schwarzbach J, Serences JT, Carlson RL, Steinmetz MA, Pekar JJ, Courtney SM. Transient neural activity in human parietal cortex during spatial attention shifts. Nature Neuroscience. 2002; 5:995–1002. [PubMed: 12219097]

Zangemeister WH, Canavan AGM, Hoemberg V. Frontal and parietal transcranial magnetic stimulation (TMS) disturbs programming of saccadic eye movements. Journal of the Neurological Sciences. 1995; 133:42–52. [PubMed: 8583231]

highlights

- The functional connectivity between PPC and visual cortices was examined.
- TMS and event-related fast optical imaging (EROS) were used concurrently.
- EROS was used to image the spread of TMS-induced activity to occipital cortex.
- Activation of extrastriate visual cortex was found 24 to 48 ms following TMS.

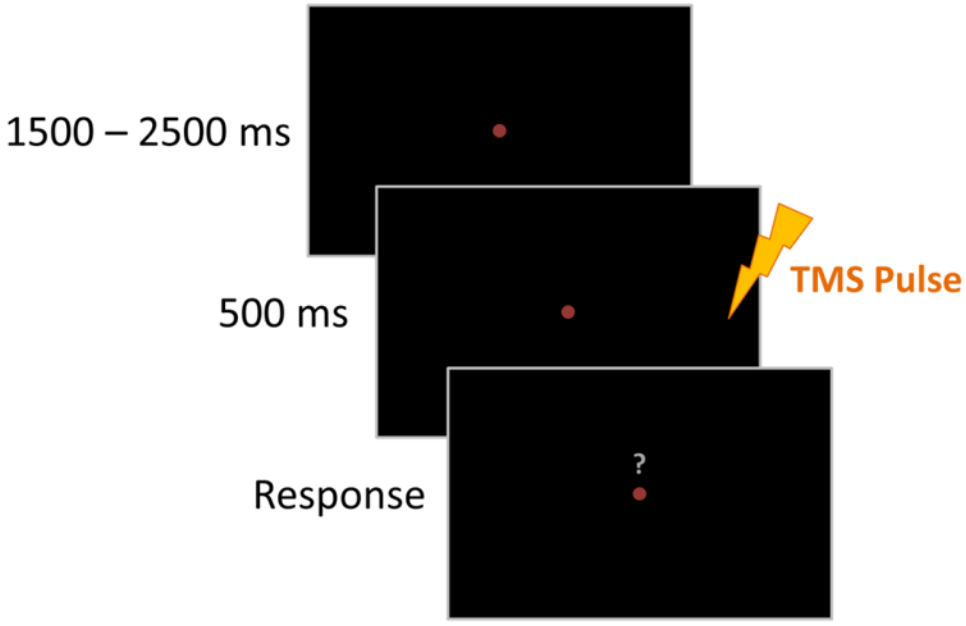

fig 1

Figure 1.
Trial schematic illustrating stimuli and timing of TMS pulses.

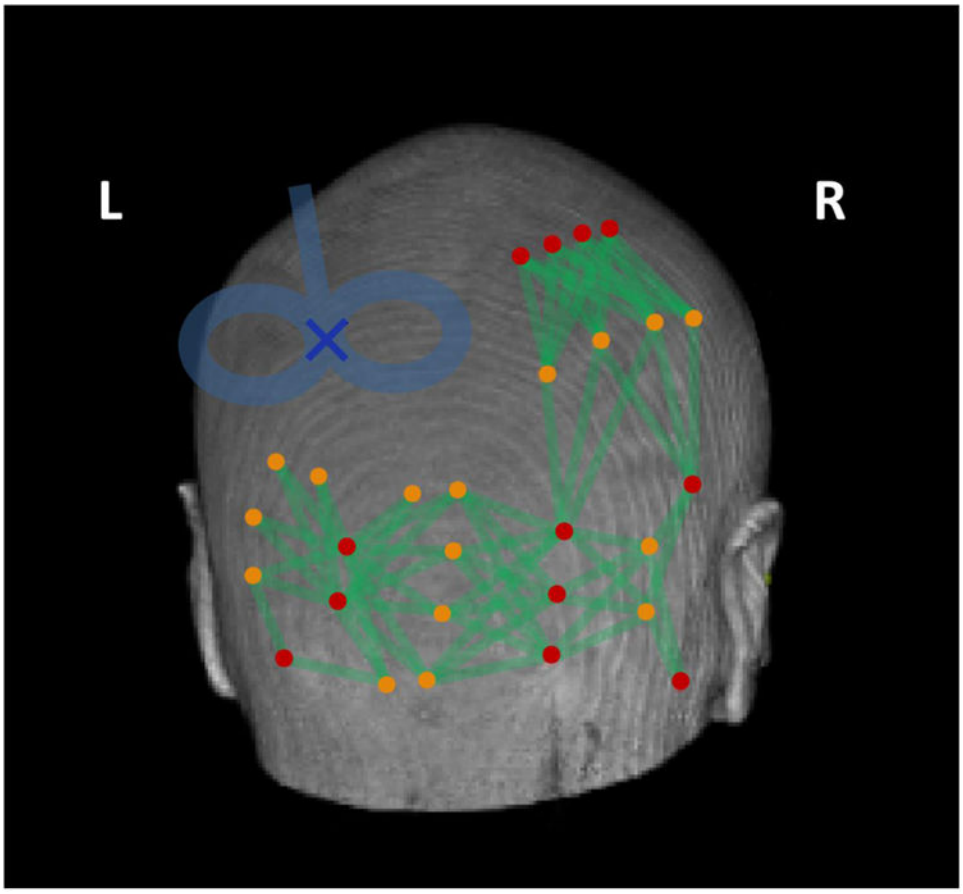

Figure 2.

Posterior view of a three-dimensional reconctruction of the optical montage from a representative subject. Optode locations are displayed on a scalp render derived from an anatomical MRI. Optode locations are shown as red (sources) and yellow (detectors) dots. Green lines indicate souce-detector pairs used to form optical channels in a typical subject. Location of P3 TMS is indicated by a blue ‘X’.

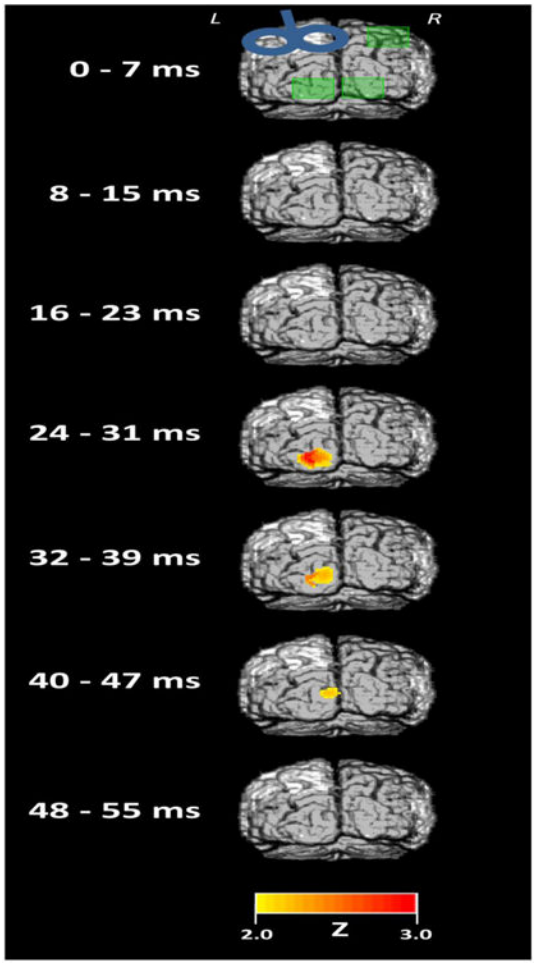

Figure 3.

Time course of TMS-evoked fast optical responses (P3 TMS versus control site TMS). Statistical parametric maps are surface projected onto a posterior view of a template Talairach brain and thresholded for display at a z-score of 2.0. Dark gray regions of the template brain denote regions of usable coverage from the optical montage whereas light gray areas indicate areas without coverage. Analysis ROIs are highlighted on the template brain as green boxes.

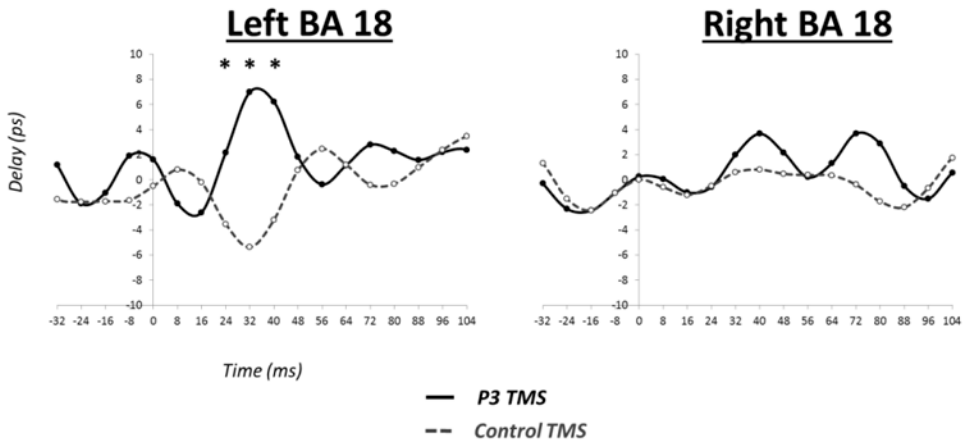

Figure 4.

Fast optical waveforms (phase delay) from left and right BA 18. Left BA 18 waveforms are the mean time series data derived from the mean of peak voxels achieving statistical significance within the left hemisphere ROI. Right BA 18 waveforms are mean time series data derived from homologous voxels in the right hemisphere. Asterisks represent statistically significant time points ($p < .05$).