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Attention modulates specific motor cortical circuits recruited by transcranial magnetic stimulation

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Abstract

Skilled performance and acquisition is dependent upon afferent input to motor cortex. The present study used short-latency afferent inhibition (SAI) to probe how manipulation of sensory afference by attention affects different circuits projecting to pyramidal tract neurons in motor cortex. SAI was assessed in the first dorsal interosseous muscle while participants performed a low or high attention demanding visual detection task. SAI was evoked by preceding a suprathreshold transcranial magnetic stimulus with electrical stimulation of the median nerve at the wrist. To isolate different afferent intracortical circuits in motor cortex SAI was evoked using either posterior-anterior (PA) or anterior-posterior (AP) monophasic current. In an independent sample, somatosensory processing during the same attention demanding visual detection tasks was assessed using somatosensory evoked potentials (SEP) elicited by median nerve stimulation. SAI elicited by AP TMS was reduced under high compared to low visual attention demands. SAI elicited by PA TMS was not affected by visual attention demands. SEPs revealed that the high visual attention load reduced the fronto-central P20-N30 but not the contralateral parietal N20-P25 SEP component. P20-N30 reduction confirmed the visual attention task altered sensory afference. The current results offer further support that PA and AP TMS recruit different neuronal circuits. AP circuits may be one substrate by which cognitive strategies shape sensorimotor processing during skilled movement by altering sensory processing in premotor areas.

Keywords

Transcranial Magnetic Stimulation; monophasic; current direction; Indirect waves; Motor; Attention

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Disclosures

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Introduction

Afferent input to motor cortex is integral to the acquisition and performance of motor skills. Short-latency afferent inhibition (SAI) (Tokimura et al., 2000) offers a method to probe the modulatory effects of somatosensory afference upon motor cortex excitability and plasticity. SAI involves transcranial magnetic stimulation (TMS) over motor cortex timed to coincide with the arrival of somatosensory afference evoked by stimulation of the corresponding peripheral nerve (~20ms for distal muscles of the hand). The inhibition evoked by the somatosensory afference is cortical in origin with spinal excitability unaffected (Tokimura et al., 2000). That at least part of the SAI network is driven by somatosensory afference to motor cortex is evidenced by increasing inhibition as the intensity of the peripheral nerve stimulus is increased (Fischer and Orth, 2011). Further, the positive relationship between the N20-P25 somatosensory evoked potential (SEP) and magnitude of SAI suggests that at least part of the network mediating SAI is dependent upon thalamo-cortical projections to somatosensory cortex (Bailey et al., 2016). Although there is a strong relationship between somatosensory afference and SAI, SAI is a malleable phenomenon modulated by movement timing and the relevance of a muscle to voluntary movement (Voller et al., 2006; Asmussen et al., 2013; Asmussen et al., 2014). Central cholinergic involvement, in addition to GABA_A, in the generation of SAI (Ziemann et al., 2014) makes it a potential method to probe the effect of cognition on motor cortex excitability through attention-related afferent modulation.

To date all the aforementioned studies have quantified SAI by pairing posterior-anterior (PA) monophasic magnetic stimulation with peripheral electrical stimulation. However, it has been demonstrated that SAI evoked with less frequently employed anterior-posterior (AP) monophasic current isolates different circuits of inhibitory neurons (Ni et al., 2011). Functionally, networks recruited by PA and AP stimulation have been differentially linked model-free and model-based learning (Hamada and Galea, 2014). AP sensitive, but not PA sensitive, circuits mediate individual responsiveness to plasticity inducing protocols like theta burst stimulation (Hamada et al., 2013) that are mechanistically similar to those that underlie motor learning (Censor and Cohen, 2011). These same plasticity inducing protocols are sensitive to attention demands and allocation (Stefan et al., 2004; Conte et al., 2007; Kamke et al., 2012; Kamke et al., 2014) suggesting that the AP circuit may be sensitive to attention. Suppressing cortical areas linked to cognitive control, like dorsolateral prefrontal cortex, to minimize their influence of sensorimotor processing enhances procedural learning (Galea et al., 2010; Zhu et al., 2015). The common involvement of AP sensitive circuits in mediating SAI and plasticity inducing protocols raises the possibility that at least some of the networks involved in generating SAI may reflect a volitional cognitive modulation of sensory-motor processing (Paul and Ashby, 2013).

The current study assessed the effect of attention load on the specific afferent intracortical motor circuits recruited by different current directions. SAI was elicited using either PA or AP TMS to preferentially recruit distinct motor cortical circuits (Ni et al., 2011) during a visual detection task of varying attentional demand. While it is well known that PA SAI scales with peripheral stimulation intensity, somatosensory afference can similarly be scaled by intrinsic factors such as attention (Staines et al., 2002; Meehan and Staines, 2009) and

movement intention (Legon et al., 2008; Legon et al., 2010). Tasks with high perceptual loads draw attention resources away from task-irrelevant sensory processing leading to suppression of the irrelevant afference (Lavie, 2005). In the somatosensory system such attention related suppression can occur as early as the N20-P25 thalamo-cortical afferent projections (Staines et al., 2002; Legon and Staines, 2006; Meehan et al., 2009), the same projections shown to underline SAI magnitude (Bailey et al., 2016). Therefore, we hypothesized that an increasingly attention demanding visual detection task would reduce somatosensory afference and thereby reduce SAI elicited by both PA and AP sensitive networks. We further hypothesized that any reduction would be greater for AP SAI. The latter hypothesis was based upon a collection of past observations involving the relationship between theta burst stimulation and late I-wave recruitment (Hamada et al., 2013), reduced efficacy of theta burst stimulation when attention is withdrawn (Kamke et al., 2012) and that SAI predominantly works on later I-waves more readily recruited by AP TMS (Tokimura et al., 2000; Ni et al., 2011). In a second independent experiment, we quantified the change in the parietal N20-P25 and frontal P20-N30 SEPs to index somatosensory gating induced by the different attention demands of the visual detection tasks.

Experimental Procedures

Participants

Twelve self-reported right-handed adults participated in the original TMS experiment assessing SAI under different visual attention demands (Experiment 1; 6 males, 6 females, 22 ± 5 years). An independent sample of thirteen self-reported right-handed adults participated in the post-hoc SEP experiment (Experiment 2; 6 males, 7 females, 22 ± 5 years). All participants across both experiments provided written informed consent; the Institutional Review Board of the University of Michigan Medical School (IRBMED) approved the study protocol.

Visual Detection Task

For both experiments visual attention load was manipulated using a visual detection task with two levels of difficulty (Schwartz et al., 2005; Kamke et al., 2012). The visual detection task required participants to monitor a stream of different color upright and inverted crosses presented at a rate of 4Hz. For the low attention task participants counted the number of red crosses in the stream regardless of orientation (Figure 1A). In the high attention variant participants counted the number of upright yellow or inverted green crosses (Figure 1B). Participants verbally reported the count at the end of the trial. For both experiments behavioral performance was assessed by comparing mean accuracy across the low and high attention load variants of the visual detection task.

Transcranial Magnetic Stimulation (TMS)

For Experiment 1, motor evoked potentials (MEP) elicited by TMS were recorded using LabChart 7 software in conjunction with a Dual BioAmp and PowerLab 8/30 acquisition system (AD Instruments, Colorado Springs, CO). Participants were seated with both arms resting on a pillow placed upon their lap. Surface electromyography electrodes (Ag-AgCl) were placed over the right first dorsal interosseous muscle using a tendon-belly montage.

Surface electromyography recording was triggered using a 5V TTL pulse with an epoch of –0.3 to 0.5s. During acquisition, data were amplified (x1000), digitized (x40000Hz) and filtered (band pass filtered 5–1000Hz, notch filter – 60Hz). Surface electromyography data were subsequently down-sampled to 5000Hz during offline analysis. The MEP was defined as the peak-to-peak amplitude of the maximal electromyographic response between 20 to 50ms post-TMS stimulation. Trials where baseline root mean square error (–50 to 0ms) in the first dorsal interosseous muscle exceeded 15 μ V were excluded from subsequent analysis. Less than 2% of all trials were excluded as a result of excessive muscle activity during the baseline period.

TMS was delivered using a MagVenture MagPro X100 with option stimulator (MagVenture Inc., Atlanta, GA) and a figure-8 coil (MC-B70). Two different current configurations were delivered. For posterior-anterior (PA) stimulation the coil was held ~45° to the midline and current direction specific as “reverse” using the stimulator’s onboard software (Figure 1D). For anterior-posterior (AP) stimulation the coil orientation was identical with that for PA stimulation but current direction was current was set to “normal” via the stimulator’s onboard software (Figure 1D).

The left first dorsal interosseous motor cortical hotspot was defined as the scalp position that elicited the largest and most consistent response following PA stimulation. The location and trajectory of the coil on the scalp at the hotspot was recorded using the BrainSightTM stereotactic system (Rogue Research, Montreal, QC). The same hotspot was used for AP stimulation (Sakai et al., 1997). Resting motor threshold was independently defined for the PA and AP induced currents as the percentage of stimulator output (to the nearest 1%) that elicited an MEP of 50 μ V peak-to-peak on 10 out of 20 trials (Rossini et al., 2015). TMS intensity for SAI was set to the stimulator output that elicited a peak-to-peak MEP amplitude of ~1mV (in the absence of peripheral stimulation) for each current direction.

Short-Latency Afferent Inhibition (SAI)

SAI consisted of a peripheral electrical stimulus paired with TMS. Electrical stimulation was delivered using a DS7A constant current high voltage stimulator (Digitimer North America LLC, Fort Lauderdale, FL). Stimulation was applied over the median nerve at the right wrist (constant current square wave pulse, 0.2ms duration, cathode proximal). Electrical stimulation intensity was set to the intensity to produce a slight thumb twitch (Abbruzzese et al., 2001). The electrical stimulus intensity was 2.8 $\pm$ 0.7 times sensory threshold. Sensory threshold was defined as the intensity at which participants correctly identified the presence/absence of stimulation on five out of 10 trials. Electrical stimulation preceded TMS stimulation by 21ms, an ISI known to produce the strongest inhibition for PA (Tokimura et al., 2000; Ni et al., 2011) and AP SAI (Ni et al., 2011).

Somatosensory Evoked Potentials (SEP)

For Experiment 2, SEPs were derived from electrical stimulation to the right median nerve while the participant completed the visual attention task. Median nerve stimulation consisted of square wave pulses (0.5ms duration) delivered through surface electrodes fixed to the wrist (DS-7A constant current stimulator). Median nerve stimulus intensity was set to motor

threshold and the M-wave was monitored via surface electromyography (EMG) at the thenar eminence (2000x amplification, 1–200Hz bandpass filtered, digitized at 1200 Hz, g.tec g.USBamp, g.tec Neurotechnology, Rensselaer, NY).

Electroencephalographic data were recorded from Fz, Cz, Pz, Oz, C3, C4, Cp3, Cp4 and A1 (g.Sahara active dry electrodes, g.UBSamp). Electrodes were positioned consistent with the international 10–20 system for electrode placement and referenced to average mastoids (<5k Ω impedance, 20000x amplification, 1–200Hz bandpass filtered, 1200 Hz digitization). SEPs were extracted using the EEGLab toolbox (Institute for Neural Computation, University of California – San Diego, San Diego, CA) for MATLAB v2014b (The MathWorks, Natick, MA) environment. Approximately 380 artifact-free epochs per condition per subject were time locked to the median nerve stimulus. Peak-to-peak amplitudes for the frontal P20-N30 and parietal N20-P25 were extracted from Fz and Cp3 respectively.

Experimental Design and Procedure

Experiment 1 consisted of a single session. SAI was elicited while participants completed thirty second epochs of the low and high attention tasks. During each 30s epoch four TMS stimuli were delivered. The first TMS pulse occurred ~5s after the start of the 30s epoch with each subsequent pulse occurring at an interval of ~8 seconds (Figure 1C). Participants completed six epochs involving PA stimulation in the absence of peripheral nerve stimulation and six epochs where PA stimulation was preceded by median nerve stimulation. The same process was repeated for AP stimulation. In total the six 30s epochs yielded twenty-four unconditioned and twenty-four peripherally conditioned trials per combination of current direction and visual detection task. The order of conditioned/unconditioned epochs, current direction and visual detection task variant was counterbalanced across participants.

Experiment 2 also consisted of a single session. SEPs were elicited at 4Hz during twenty second epochs of the low and high attention demanding tasks. Five 20s epochs were completed for each variant of the visual detection task. During each epoch median nerve stimulation occurred at 4Hz providing 400 stimuli per attention level. The order of the visual detection task was randomized across participants. It should also be noted that the visual detection tasks were part of a bigger study that also included eliciting SEPs during performance of a Sternberg short-term memory task (Sternberg, 1966). The order of attention versus working memory condition was counterbalanced across participants.

Data analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows (v23, IBM Corp. Armonk, NY).

For Experiment 1, behavioral performance was assessed using a linear mixed model with the factors Load (Low, High) and Current Direction (PA, AP). The factor Subject was included as a random effect to account for different intercepts across participants.

Motor cortical physiology was assessed in two steps. First, we performed a linear mixed model to compare unconditioned MEP amplitude across Current Direction (AP, PA) and Load (Low, High) to detect any differences in unconditioned MEP amplitude. Second, to assess the effect of attention load on each SAI evoked with each current direction the same linear mixed model was employed with the dependent variable SAI. SAI was derived as a percentage of unconditioned MEP amplitude. Lower values for SAI indicate higher levels of MEP suppression by the somatosensory afferent volley.

For Experiment 2, behavioral performance and SEPs for the low and high attention demanding visual detection tasks were assessed using paired-samples t-tests.

Results

Experiment 1 – TMS under varying visual attention demands

Mean accuracy in the visual detection task was higher for the low compared to high attention task [Main Effect_{Load}: $F_{1,19}=15.83$, $p=0.001$; Low= $83\pm 7\%$, High= $64\pm 7\%$]. Accuracy was consistent across current direction as neither the interaction [$F_{1,34}=0.06$, $p=0.82$] nor the main effect of Current Direction [Interaction: $F_{1,28}=0.18$, $p=0.68$] were significant.

Figure 2A and 2B shows the group averaged traces ($n=12$) of conditioned and unconditioned MEPs for each current direction. Resting motor threshold for PA stimulation and AP stimulation was $45\pm 4\%$ (mean $\pm$ standard deviation) and $60\pm 7\%$ of stimulator output respectively. The stimulation intensity to elicit an MEP of 1mV using PA and AP stimulation was $54\pm 9\%$ and $71\pm 12\%$ of stimulator output respectively. Consistent with past work the latency of MEPs was significantly longer for AP compared to PA stimulation [Main effect_{Current Direction}: $F_{1,17}=19.68$, $p=0.0004$, PA= 22 ± 0.6 ms, AP= 25 ± 0.7 ms]. The longer latencies for AP current were consistent across visual attention loads given the absence of a significant main effect of Load [$F_{1,21}=0.29$, $p=0.60$] or Load x Current Direction interaction [$F_{1,35}=0.21$, $p=0.65$].

There were no differences in unconditioned MEP amplitude across current direction or attention load. The Current Direction x Load interaction [$F_{1,32}=0.04$, $p=0.85$] and main effects of Current Direction [$F_{1,38}=0.35$, $p=0.56$] and Load [$F_{1,44}=0.11$, $p=0.74$] failed to reach significance. A Stimulation Type x Load linear mixed model confirmed SAI was present across all condition and loads as conditioned MEPs were significantly reduced compared to unconditioned MEPs for both PA [Main Effect_{Stimulation Type}: $F_{1,16}=36.21$, $p=0.00002$] and AP current [Main Effect_{Stimulation Type}: $F_{1,48}=20.36$, $p=0.0004$]. However, the magnitude of SAI was evoked by PA and AP stimulation was differentially impacted by attention load [Interaction_{Load x Current Direction}: $F_{1,32}=5.96$, $p=0.02$]. The significant interaction was driven by a reduction in SAI from low to high load when MEPs were evoked using AP current ($p=0.001$) but no effect of load for MEPs evoked using PA current ($p=0.56$) (Figure 2C).

Experiment 2 – Somatosensory gating under varying visual attention demands

Consistent with Experiment 1, mean accuracy was higher for the low compared to high load condition of the visual detection task [$t_{1,12}=4.47$, $p=0.001$; Low= $90\pm 6\%$, High= $63\pm 4\%$].

Figure 3A and 3B show the group averaged SEPs (n=13) from Fz and CP3. Parietal N20-P25 peak-to-peak amplitude was not different across the low and high attention demanding visual detection tasks [$t_{1,12}=0.47$, $p=0.65$] (Figure 3C). In contrast, frontal P20-N30 peak-to-peak amplitude was significantly reduced during the high compared to low attention demanding visual detection task [$t_{1,12}=2.60$, $p=0.02$] (Figure 3C).

Discussion

The current study used SAI to investigate the effect of visual attention demands upon PA-sensitive and AP-sensitive afferent intracortical circuits. The novel finding is that a visual detection task that draws greater attentional resources reduces AP SAI but had no effect upon PA SAI. The reduction in AP SAI appears to be driven by reduced processing of sensory afference as the same attention demanding visual detection task reduced the frontal P20-N30 SEP component, although it had no effect upon the parietal N20-P25 SEP component.

The current study is the first study to investigate the effects of cognitive demands, specifically crossmodal attention, upon the corticospinal output generated by PA and AP stimulating current. It is well-established that the descending volley induced by TMS results from a series of trans-synaptic projections onto the corticospinal neuron termed I-waves (Di Lazzaro et al., 1998; Di Lazzaro et al., 2012). Though the peripheral conditioning stimulus in SAI acts to suppress later I-waves (Tokimura et al., 2000; Di Lazzaro et al., 2005) the degree of suppression (Ni et al., 2011) as well as the latency of the late I-waves (Di Lazzaro et al., 2001) generated by PA and AP current suggest that different neuronal populations are involved in generating the I-waves elicited by each current direction. The specificity of AP SAI to the attention demands of the visual detection task is consistent with the notion that PA and AP current directions recruit differential circuits of neurons projecting to the pyramidal tract neurons. The sensitivity of AP SAI to attention demands appears to reflect a substrate by which cognitive functions and strategies may shape motor cortical excitability. AP SAI may provide a marker of the impact of attentional deficits, like spatial neglect, or compensatory strategies following acquired brain injuries, such as stroke, on motor cortex function.

The reduction of the P20-N30 frontal SEP component under high visual attention load in Experiment 2 confirms that our visual detection task manipulated sensory afference. The frontal P20-N30 elicited by median nerve stimulation reflects sensorimotor integration of afferent input and has been localized to the supplementary motor area and precentral gyrus (Desmedt and Cheron, 1981). However, the absence of a task-related effect upon the parietal N20-P25, localized to Areas 3B/1 of the primary somatosensory cortex (Allison et al., 1991), suggests that afferent modulation was network specific. Relatively more is known about the relationship between afferent input and PA SAI than for AP SAI. PA SAI is directly related to the magnitude of the thalamo-cortical somatosensory afferent relay, as indexed by the N20-P25 SEP component (Bailey et al., 2016). No direct assessment of the relationship between somatosensory afferent volley and AP SAI has been conducted however, models of I-wave generation posit a premotor origin (Di Lazzaro et al., 2012; Volz et al., 2014). A premotor origin for AP SAI would be consistent with the reduction in AP

SAI under high loads of visual attention (Experiment 1) and the specific reduction of the P20-N30 SEP component (Experiment 2). One limitation to the current study is that SAI and SEPs were recorded across two separate samples. Therefore, we cannot directly correlate the extent of reduced AP SAI and frontal P20-N30 suppression to establish a causal relationship. As such the link between the effect of the visual detection task on SAI magnitude and SEP amplitude is indirect. However, the concurrent insensitivity of PA SAI (Experiment 1) and the parietal N20-P25 SEP component (Experiment 2) do suggest that difference sensory afferent pathways map on to specific intracortical motor circuits projecting to pyramidal tract neurons. Future work investigating the differential properties of PA and AP sensitive circuits and their functional significance is needed.

Whether the pathways mediating PA SAI are unequivocally insensitive to attention cannot be definitively stated. Attention can exert its influence at many levels of the sensory afferent pathway depending upon task demands as well as the spatial and temporal properties of the competing afference. While the current visual detection task did not influence PA SAI or the N20-P25 SEP component, somatosensory input was passive and did not share spatial or temporal characteristics with the visual detection task. Somatosensory cortex activation (Meehan and Staines, 2007, 2009) and more specifically, N20-P25 amplitude (Meehan et al., 2009), is reduced in the presence of a strong somatosensory input sharing spatial and temporal characteristics during visuomotor transformations. Given the relationship between N20-P25 SEP amplitude and PA SAI established by Bailey et al. (2016), it is possible that stronger spatial and temporal competition between vision and somatosensation could lead to changes in somatosensory afferent processing in both the PA and AP sensitive circuits. Nonetheless, the attentional dissociation observed here is consistent with a differential functional role of afferent input to the PA and AP I-wave circuits. PA SAI is reduced during finger movement with the reduction onset occurring during the preparatory phase (Asmussen et al., 2013) and involved in the surround inhibition of muscles not involved in the planned movement (Voller et al., 2006; Asmussen et al., 2014) suggesting a role in spatial and temporal priming of actions. Again, very little research has investigated the functional significance of the AP circuit however, the selective sensitivity of AP SAI to our attention manipulation is consistent with a modulatory mechanism that provides a substrate for cognitive influence upon selected actions. Future work investigating the functionality of the AP SAI circuit is needed. Additionally, pharmacological investigations of the susceptibility of PA and AP SAI to cholinergic and GABA_A-ergic agonists and antagonists are needed.

The changes in AP SAI observed when attention is drawn to a visual task in the absence of strong spatial and temporal visual-somatosensory links raises important considerations tied to TMS variability in healthy and clinical populations. Although the magnitude of PA SAI does not correlate with intermittent theta burst after-effect (Young-Bernier et al., 2014) no such study has been conducted for AP SAI. The absence of a correlation for PA SAI and intermittent theta burst stimulation is not surprising given previous work demonstrated the earlier I-waves predominantly recruited by PA stimulation are not a strong predictor of theta burst after-effect (Hamada et al., 2013). However, Hamada et al. (2013) did observe a strong relationship between late I-wave recruitment, preferentially recruited by AP stimulation, and theta burst after-effect. Further, the efficacy of the intermittent theta burst (Kamke et al., 2012), in addition to traditional the repetitive TMS (Conte et al., 2007) and paired

associative stimulation (Stefan et al., 2004; Kamke et al., 2012; Kamke et al., 2014) plasticity inducing protocols are known to be sensitive to spatial and crossmodal attention. Therefore, future work is needed to determine if the selective reduction of AP SAI under high demands of visual attention observed here possibly reflects a state dependent mediator of the variability in how TMS recruits pyramidal neurons and the after-effects of plasticity inducing protocols. Strong consideration of attentional control is warranted, even when TMS is delivered at rest, as covert cognitive influence could alter the state of targeted circuits even in the absence of overt somatosensory afference (Pfurtscheller, 1992).

An interesting result from the current study is that we did not observe a difference in the magnitude of SAI across the PA and AP current regardless of visual attention demands. Ni et al. (2011) demonstrated that at rest, in the absence of any task, peak SAI was greater for PA compared to AP current. However, we did not observe any current specific difference in SAI amplitude despite latency differences consistent with past work. Similar to past work we matched the test stimulus MEP to 1mV across current direction so differences in baseline MEP amplitude cannot account for this discrepancy. It is possible that the mere presence of a concurrent task, independent of the attention demands, may have had a normalizing effect across current direction through general increased arousal distinct from the attention effect associated with task load. However, it is also plausible that the discrepancy is driven by the conditioning stimulus intensity. This past work demonstrated significantly greater SAI for PA compared to AP current starting at a conditioning stimulus intensity of 3x sensory threshold (Ni et al., 2011). We based our stimulation intensity off of motor threshold which equated to 2.7x sensory threshold.

The current study demonstrates PA and AP sensitive circuits are distinct and have differential sensitivity to visual attention demands. The AP circuit likely reflects afferent influence at the level of supplementary/premotor cortex that is fed to motor cortex via cortico-cortical connectivity. Influence over afferent processing in the AP sensitive circuit may reflect one pathway by which declarative strategies may influence procedural processing in motor control and learning.

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Highlights

1. SAI evoked by monophasic AP but not PA stimulation is reduced by increasing the attention load of a visual detection task.
2. Differential sensitivity to attention supports recruitment of distinct neuronal mechanisms by PA and AP stimulation.
3. Reduced frontal P20-N30 SEP under high attention supports AP recruitment of premotor cortico-cortical projections.
4. AP neuronal mechanisms may be a functionally distinct substrate for cognitive modulation of procedural motor system.

Figure 1.

Visual detection task and experimental protocols. For both experiments the visual detection task consisted of the rapid presentation (4Hz) of a sequence of colored crosses. Crosses were either upright or inverted. A) The low attention load variant required participants to count the number of red crosses regardless of orientation (arrow indicates target). B) The high attention load variant required participants to count based upon color and orientation. For example, participants were required to count the number of upright yellow or upside down green crosses in the sequence. C) Example of the protocol for a single trial in Experiment 1. During the 30s trial four single pulse stimuli were presented over the left first dorsal interosseous motor cortical hotspot. Stimuli were separated by approximately 8s. Each of the four pulses in a given trial either consisted of unconditioned single pulse stimuli or single pulses conditioned by peripheral median nerve stimulation. Twelve 30s epochs were completed for each combination of current direction and visual detection task load. Six epochs involved unconditioned stimulation. The remaining six involved stimulation condition by peripheral stimulation of the contralateral median nerve at the wrist. D) Depiction of the different current directions for PA and AP TMS. The dark grey arrows indicate the induced current in the brain. The white curved arrows on the TMS coil indicate the direction of the TMS coil current. Note, the induced current in the brain flows in the opposite direction to the coil current. The TMS coil current direction was controlled by the stimulator's onboard software. FDI EMG – first dorsal interosseous electromyography electrode, MNS – median nerve stimulation.

Figure 2.

A) Unconditioned and conditioned group averaged motor evoked potentials elicited by PA stimulation during the low (left panel) and high (right panel) attention demanding visual detection task. B) Unconditioned and conditioned group averaged motor evoked potentials elicited by AP stimulation during the low (left panel) and high (right panel) attention demanding visual detection task. C) SAI elicited under varying attention load evoked by different magnetic stimulation. Amplitudes are expressed as a percentage of the unconditioned motor evoked potential amplitude. Higher values represent lower levels of SAI. The group average across low and high attention load for each current direction (black line) is overlaid on individual data (grey lines). Error bars represent standard error of the mean. *denotes significant contrast ($p < 0.05$).

Figure 3.

A) Grand average SEP waveform recorded from Fz while participants performed either the low or high attention demanding visual detection task. B) Grand average SEP waveform recorded from Cp3 while participants performed either the low or high attention demanding visual detection task. C) Peak-to-peak amplitudes of the parietal N20-P25 and frontal P20-N30. The group average across low and high attention load for each SEP component (black line) is overlaid on individual data (grey lines). Error bars represent standard error of the mean. *denotes significant contrast ($p < 0.05$).