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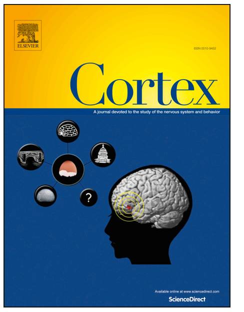

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PII: S0010-9452(18)30071-6

DOI: 10.1016/j.cortex.2018.03.002

Reference: CORTEX 2262

To appear in: *Cortex*

Received Date: 7 August 2017

Revised Date: 21 February 2018

Accepted Date: 1 March 2018

Please cite this article as: McDowell T, Holmes NP, Sunderland A, Schürmann M, TMS over the supramarginal gyrus delays selection of appropriate grasp orientation during reaching and grasping tools for use, *CORTEX* (2018), doi: 10.1016/j.cortex.2018.03.002.

TMS over the supramarginal gyrus delays selection of appropriate grasp orientation during reaching and grasping tools for use

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Abstract

Tool use, a ubiquitous part of human behaviour, requires manipulation control and knowledge of tool purpose. Neuroimaging and neuropsychological research posit that these two processes are supported by separate brain regions, ventral premotor and inferior parietal for manipulation control, and posterior middle temporal cortex for tool knowledge, lateralised to the left hemisphere. Action plans for tool use need to integrate these two separate processes, which is likely supported by the left supramarginal gyrus (SMG). However, whether this integration occurs during action execution is not known. To clarify the role of the SMG we conducted two experiments in which healthy participants reached to grasp everyday tools with the explicit instruction to use them directly following their grasp. To study the integration of manipulation control and tool knowledge within a narrow time window we mechanically perturbed the orientation of the tool to force participants to correct grasp orientation 'on-line' during the reaching movement. In experiment 1, twenty healthy participants reached with their left hand to grasp a tool. Double-pulse transcranial magnetic stimulation (TMS) was applied, in different blocks over left or right SMG at the onset of perturbation. Kinematic data revealed delayed and erroneous online correction after TMS over left and right SMG. In Experiment 2 twelve participants reached, in different blocks, with their left or right hand and TMS was applied over SMG ipsilateral to the reaching hand. A similar effect on correction was observed for ipsilateral stimulation when reaching with the left and right hands, and no effect of or interaction with hemisphere was observed. Our findings implicate a bilateral role of the SMG in correcting movements and selection of appropriate grasp orientation during reaching to grasp tools for use.

Key Words: Tool use, Visuomotor Control, Grasp Orientation, TMS, SMG.

Tool use is an integral part of human day to day behaviour (Osiurak, Jarry, & Le Gall, 2010; Tomasello, 1999). Neuroimaging (Brandi, Wohlschläger, Sorg, & Hermsdörfer, 2014; Johnson-Frey, Newman-Norlund, & Grafton, 2005; Lesourd, Osiurak, Navarro, & Reynaud, 2017; Orban & Caruana, 2014; Przybylski & Kroliczak, 2017; Reynaud, Lesourd, Navarro, & Osiurak, 2016) and neuropsychological studies (Buxbaum, 2001; Buxbaum & Kalénine, 2010; Johnson-Frey, 2004; Ochipa, Rothi, & Heilman, 1989) have implicated a distributed left hemispheric network for controlling interactions with familiar tools. Temporal (i.e., the posterior middle temporal gyrus) and ventral-pre-motor and inferior parietal (Brandi et al., 2014; Orban & Caruana, 2014; Vingerhoets, 2014) structures in this network seem to serve different aspects of behaviour pertaining to tools, but must be functionally integrated to successfully carry out tool related actions (Johnson-Frey et al., 2005).

Consistent with this network, a variation on the influential two visual streams model (Goodale & Milner, 1992; Milner & Goodale, 2008) has been used to explain the cognitive processes behind tool use behaviour. This variation proposes a separation of the dorsal stream (originally the “where” pathway) into the ventro-dorsal and dorso-dorsal pathways (Binkofski & Buxbaum, 2013; Buxbaum, Kyle, Tang, & Detre, 2006; Daprati & Sirigu, 2006; Rizzolatti & Matelli, 2003; Vingerhoets, Acke, Vandemaele, & Achten, 2009). Dependent on the goal of hand-object interaction (either acting on an object or acting with it), the behaviour will be mediated by one of these two dorsal pathways (Vingerhoets, 2014). In the case of ‘acting on’ an object, for example, moving from one location to another, action execution will be carried out by the dorso-dorsal stream. Projecting from visual cortices V3A via superior parietal lobule (SPL) to dorsal premotor cortex (PMd) (Binkofski & Buxbaum, 2013; Brandi et al., 2014; Vry et al., 2012), the dorso-dorsal stream is argued to place both effector limb and object into a single coordinate system, while the object's intrinsic (size and shape) and extrinsic (location and orientation) visual properties guide action towards it. This system facilitates appropriate grasp to allow transportation of the object to a goal location (Johnson & Grafton, 2003), such as placing a fork in a drawer. These processes seem to be mediated by the SPL and the anterior intraparietal sulcus (aIPS) (Brandi et al., 2014; Daprati & Sirigu, 2006).

By contrast, interactions with objects that are to be ‘acted with’ are mediated by the ventro-dorsal stream, projecting from visual cortices (e.g. V5/MT), via inferior parietal lobule (IPL) to ventral pre-motor cortex (PMv) (Binkofski & Buxbaum, 2013; Rizzolatti & Matelli, 2003; Vry et al., 2012, 2015). When engaging with objects that are to be ‘acted with’, further conceptual input is required to carry out movements (Vingerhoets, 2014). Two approaches argue that this input is either reliant on stored semantic representations of objects and associated manipulations based on previous use (Buxbaum, 2001; Buxbaum & Kalénine, 2010; Rothi, Ochipa, & Heilman, 1991; Thill, Caligiore, Borghi, Ziemke, & Baldassarre, 2013), or reasoning about an object’s use based on its perceived properties dependent on the action goal (Badets & Osiurak, 2015; Goldenberg & Spatt, 2009; Osiurak, Jarry, & Le Gall, 2011; Osiurak, Roche, Ramone, & Chainay, 2013). Although this issue is unresolved (for review see Osiurak & Badets, 2016), both approaches indicate that this input informs selection of an appropriate grasp that allows the use of the object. For example, when reaching to use a fork, knowledge of how to use it efficiently informs the appropriate grasp orientation; by the handle with the tines facing away from the hand. Although there is disagreement on the nature of this conceptual input, both approaches posit that the left IPL in the ventro-dorsal pathway is likely the locus of this knowledge (Osiurak & Badets, 2016) and integration of this conceptual input into the necessary motor transformations for use (Vingerhoets, 2014).

More specifically, the supramarginal gyrus (SMG) in the IPL, has been argued as the site of conceptual input into the ventro-dorsal stream when people direct actions towards tools to be acted with. The SMG has shown activation in a number of fMRI studies involving tool naming (Chao & Martin, 2000; Martin, Wiggs, Ungerleider, & Haxby, 1996; Okada et al., 2000) and planning and preparing tool use gestures (Johnson-Frey et al., 2005). Left hemisphere SMG activation has also been found in decision making tasks regarding context appropriate tool use actions or passively viewing skilled movements (Rumiati et al., 2004; Valyear, Cavina-Pratesi, Stiglick, & Culham, 2007). This activation is also associated with identification of tool stimuli across auditory and visual modalities of presentation (Lewis, Brefczynski, Phinney, Janik, & DeYoe, 2005) and shows a left hemisphere bias regardless of participants' handedness (Brandi et al., 2014). The middle temporal gyrus (MTG) also shows activation when people passively view tools, however, SMG activation has been shown to occur exclusively when participants are explicitly instructed to make judgements about tool use actions (Kellenbach, Brett, & Patterson, 2003). Furthermore, diffusion tensor imaging has shown a stronger left lateralised (compared to right hemisphere) connection between the SMG and the posterior MTG, regarded as a store of semantic information (Ramayya, Glasser, & Rilling, 2010). Right SMG activation has also been observed during tool action execution, while the left SMG shows activation during action execution *and* planning (Johnson-Frey et al., 2005). However, left lateralisation is more widely reported for tasks pertaining to understanding appropriate use of tools (Orban & Caruana, 2014; Peeters, Rizzolatti, & Orban, 2013; Reynaud et al., 2016). This has led to the inference that the left hemisphere has a particular role in processing functionally relevant elements of tools and associated use, such as selection of grasp (Przybylski & Kroliczak, 2017).

Examining the role of the SMG in reaching and grasping of tools, transcranial magnetic stimulation (TMS) over the left SMG (but not aIPS) has been shown to significantly delay the onset of goal oriented actions while people reach for familiar objects to be 'acted with' (Tunik, Lo, & Adamovich, 2008). Tunik and colleagues (2008) inferred that the SMG may be involved in planning movements prior to engaging in action, while aIPS monitors hand-object fit during action execution. TMS over the aIPS contralateral to the hand used, results in disruption of rapid online correction of reaching and grasping behaviour when adjustments in size or orientation are required (when applied within 65ms of object perturbation) (Tunik, Frey, & Grafton, 2005). As this experiment (Tunik et al., 2005) examined reaching behaviour towards geometric objects, these hand-object interactions arguably can be carried out without access to stored semantic representations associated with the use of such objects (Vingerhoets, 2014). Based on this, the SMG arguably provides semantic input prior to the onset of movement, that is integral to creating the action plan for use, while the aIPS monitors hand object interaction during execution. This is consistent with findings that patients with damage to left IPL show difficulty in reaching and grasping tools compared with simple geometric shapes when barrier avoidance is required (Sunderland, Wilkins, Dineen, & Dawson, 2013). However, does the SMG play a more dynamic role in monitoring the fit between hand and object, relevant to the overall goal of movement, while reaching for a tool to perform a task? Grasping an object to be acted with requires knowledge of appropriate orientation in relation to the hand. If the SMG plays a role in establishing a plan for appropriate action prior to movement, is this plan monitored during execution?

To explore this question, we developed an experimental paradigm that required participants to reach and grasp tools with the explicit intention to use them on completion of grasp. We perturbed the orientation of the tool to force an online correction of grasp orientation and applied TMS to the SMG at the onset of perturbation. The perturbation was designed to force the integration of manipulation control and tool knowledge at a specified time point.

We hypothesised that delivery of TMS over the SMG at the onset of this event would delay rotation of the hand to appropriate orientation for use (e.g., by the handle). In previous online correction tasks involving geometric objects (Tunik et al., 2005) stimulation to aIPS resulted in disruption of forearm rotation or grip aperture, while reaching was preserved. However, given the observed delays to onset of movement when engaging in goal oriented tool action with TMS applied to SMG (Tunik et al., 2008), we expect an overall increase in movement time from onset to final grasp and an increased period of slowing of movement toward target; as TMS over the SMG at the onset of tool perturbation may disrupt reassessment of the initial movement plan. This would indicate a role of the SMG in monitoring the conceptual fit between hand and object during reaching and grasping. This would also highlight the role of the

SMG as more dynamic than previously thought, being involved in monitoring movement ‘on line’ as well as during planning stages (Tunik et al., 2008).

We further hypothesised that effects of TMS would be significantly stronger for left SMG stimulation than for right. TMS was applied over the left and right SMG to examine the left lateralisation associated with tool use in neuropsychological and neuroimaging research. In neuropsychological studies, left-hemisphere damaged apraxic patients performed reaching and grasping tasks with the ipsilesional hand (Goldenberg, 2003; Goldenberg, Hartmann, & Schlott, 2003; Hermsdörfer, Li, Randerath, Goldenberg, & Johannsen, 2012; Hermsdörfer, Li, Randerath, Roby-Brami, & Goldenberg, 2013). We aimed to explore whether a corresponding but transient deficit would result from TMS to the left SMG. Therefore, participants carried out reaching and grasping of tools using their left hand for experiment 1. Additional right-hand trials were among conditions introduced in experiment 2.

1. Experiment 1

1.1. Methods

1.1.1. *Participants*

22 healthy right-handed participants (8 male, 14 female; age range 22 – 33, M = 25.00, SD = 4.63 years) were recruited from the University of Nottingham, UK (two participants' data were excluded from analysis due to motion tracking errors; this consisted of erroneous sampling of the hand orientation during reaching, characterised by artefacts which could not be corrected). Participants were eligible if they were right handed and had a structural MRI scan to allow MRI guided TMS coil placement. Handedness was assessed via the 10 item version of the Edinburgh Handedness Inventory (Oldfield, 1971). Participants were identified as having a predominantly right hand preference, with an average laterality quotient of 0.74 (SD=0.21, range 0.55-1.0). Participant safety and suitability to undergo TMS was assessed using pre-test screening (Maizey et al., 2013). Side effects or discomfort were monitored using follow up questionnaires over a 24 hour period following stimulation (Maizey et al., 2013). No side effects or discomfort attributed to TMS were reported by participants. Written informed consent was obtained from all participants prior to the experiment. The study had approval from the ethics committee of the School of Psychology, University of Nottingham, and was performed in accordance with the declaration of Helsinki (as of 2008).

1.1.2. *Apparatus*

Eight everyday tools were used as targets during the experiment. Participant familiarity with each tool was assessed prior to testing. Tools consisted of knife, fork, spoon, peeler, wrench, hammer, screwdriver and toothbrush (all plastic, ~18cm long).

The tools were held in a cradle, connected to the axle of a stepper motor to allow rapid 90° rotation. 'Hook and loop' fabric strips, applied to each end of the tool and prongs of the cradle allowed the tool to be held in a fixed position during rotation while allowing easy removal of the tool following grasp.

Targets were presented to participants in the coronal plane, 57cm from the table edge and raised 37cm from the table top. Participants' view of the target was controlled using PLATO shutter googles *(Translucent technologies, Toronto, Canada).* Motion tracking of participants' reaching movements was recorded using a Polhemus Fastrak *(Polhemus Fastrak, Colchester, Vermont, USA)* with 2 sensors sampling at 60Hz. One attached to participants' index finger; used to record kinematic data and hand orientation (Roll – degrees) during reaching. The second sensor was attached to the TMS coil to monitor position over the targets. TMS was carried out using a Magstim Rapid *(Magstim Company Ltd, Whitland, Carmarthenshire, UK).*

1.1.3. *Localisation of brain sites and TMS*

For both SMG sites the TMS coil was held tangentially to the surface of the head with the handle pointing upwards. TMS was delivered at 110% of participants' resting motor threshold (rMT). rMT was determined by delivering TMS pulses over the hand area of the right motor cortex at varying intensity until a visible twitch was observable in the left hand on approximately 50% of pulses. A double TMS pulse (100ms interpulse) was used. Ear plugs were provided to dampen the noise associated with TMS pulse discharge.

Stimulation site localisation was carried out using a Polhemus Fastrak MRI guided method of co-registration *(developed by co-author Alan Sunderland, University of Nottingham)*; using 4 fiducial landmarks (nasion, nose tip, preauricular points) sampled from the participant using the Fastrak stylus and co-registered to the digitised anatomical landmarks from a corresponding anatomical MRI for the individual. This method used digitised trajectories projecting from the cortical target that could be tracked by the stylus. A chin rest was used to maintain head position throughout trials and coil position was monitored by the experimenter.

------------------------------INSERT FIG. 1 around here-------------------------------------

1.1.4. *Design*

A repeated measures 2 x 2 x 2 x 2 design was used. The independent variables were hemisphere of SMG stimulation (left vs. right), TMS (TMS vs. noTMS), final grasp position (upright vs. inverted) and congruence between tool rotation and necessary rotation of the hand to orient from initial grasp plan to corrected grasp position (congruent vs. incongruent). Dependent variables were the overall movement time from movement onset to final grasp; percentage of movement time to 3D peak velocity of movement towards target; and a combined measure of delay in the rotation of hand to correct of orientation of grasp and erroneous rotation compared to corresponding baseline performance ('miscorrection,' measured in SD – **see Analysis 1.1.6.**). This measure was assessed by examining the roll data (rotation of the hand; see **Fig.1** and **Fig.3**). Participants completed 2 blocks of trials, with 80 trials per block. Tool rotation varied between trials in the congruence of rotation and the final grasp position required (4 rotation conditions: Inverted Incongruent (32 trials), Inverted Congruent (16), Upright Incongruent (16) and Upright Congruent (16)) (See ***Fig.* 1**). Inverted incongruent trials were identified as the most difficult during pilot testing. As we suspected the effects of TMS might be most observable for these trials, the number of trials for this condition was doubled for testing. TMS was delivered over either left or right SMG for each block, then was reversed for the second block (counterbalanced order between subjects). TMS was delivered on half of the trials in each block. Order of TMS and rotation conditions within blocks was pseudorandomised. TMS was delivered at the onset of object perturbation so as to delay reassessment of action plan selection of appropriate grasp orientation. As participants reached with their left hand, we could observe the effects of TMS to the contralateral and ipsilateral SMG. Therefore, the design negated the possibility of contralateral effects of aIPS stimulation observed by Tunik and colleagues (2005) in reaching for geometric objects being observable here.

1.1.5. *Procedure*

Participants were seated at a table with their chin positioned on the rest and the goggles positioned in front of their eyes (see ***Fig.* 2**). The index and middle fingers of participants were attached together during testing. This was to prevent participants from being able to ‘twirl’ the tool should they grasp in the incorrect orientation for use; ensuring that correction should occur prior to grasping. Participants were instructed to place their left-hand index finger on a button (30cm to the left and in line with the chin rest). PLATO goggles occluded the participants' view of stimuli between trials, ensuring that the initial orientation of the tool was not visible, forcing online correction. When provided with a verbal ‘get ready’ signal from the experimenter, participants were instructed to press and hold the button until the goggles became transparent (uniform random delay of 2 – 4 seconds between Go signal and Goggles). If the button was released prior to the goggles opening the random delay was reset to ensure no reaching began prior to viewing the target tool. Participants were instructed that as soon as the goggles became transparent they were to reach as quickly and as accurately as possible to grasp the target tool in a *manner suitable to its familiar use* while avoiding erroneous grasping. Participants were also explicitly instructed to demonstrate the use of the tool immediately after grasping.

-----------------------------INSERT FIG. 2 around here----------------------------------

Rotation onset of the target tool was locked to a forward movement (i.e., position) threshold of the motion sensor (30mm from start position) towards the cradle. If the threshold was not surpassed within 400ms of the goggles opening, an error tone was played, the goggles became opaque, and the trial was restarted. This was to prevent hesitation in reaching towards the target, ensuring rapid reaching and grasping. The tool completed its 90° rotation from onset to its f inal position within ~100ms. On TMS trials the initial TMS pulse was discharged immediately following the onset of target rotation. The second pulse occurred 100ms later, to ensure that TMS encompassed the time window of tool rotation. The TMS double-pulse was used to increase the time over which stimulation might affect function (see ***Fig.* 2**) for the duration of tool rotation. Previous findings have shown that TMS over the aIPS causes deficits in reaching and grasping correction when TMS is delivered within 65ms following perturbation (Tunik et al., 2005) suggesting the aIPS has a role in detection of error. As we wanted to disrupt the detection of error *and* potential re-integration of tool knowledge into the visuomotor transformation to carry out correction, we delivered the first TMS pulse at the onset of tool rotation and the second 100ms following, to encompass the time that this integration may occur. The efficacy of the double-pulse technique has been demonstrated in similar paradigms (Rice, Tunik, Cross, & Grafton, 2007). Participants were required to provide a brief demonstration of the tool's appropriate use immediately following completion of each grasp (*e.g.,* using the knife to cut a block of plasticine). This was to ensure that participants were grasping with *the intention of use.* Testing lasted approx. 1.5 - 2 hours across a single session with breaks.

1.1.6. **Analysis**

1.1.6.1. *Miscorrection Scores*

The roll orientation of participants' wrists during reaching was examined from the onset of target rotation to the completion of grasp. Roll data was median filtered (each data point replaced with the median of 6 neighbouring data points) to remove TMS artefacts and resampled to 100 samples to allow examination of movement correction over the percentage of movement time. Baseline correction was done for each participant by averaging the roll data from baseline trials and subtracting this for each condition. We set a threshold of ± 1 SD from the baseline to define 'miscorrections' outside of this threshold. We then examined individual trials against the baseline for each condition. Data points that fell within the baseline correction were assigned a zero value. For data points that were beyond this threshold the difference between the data point and the threshold was calculated, then divided by the SD of the baseline. This provided, for each trial, a vector of zeroes and SD values. An average of this vector (including zeros) provided the miscorrection score for each trial. This measure provides a combined indication of how late the correction was and the amplitude of incorrect rotation prior to correction, as compared to baseline. These scores were quantified as a multiple of standard deviation (see ***Fig. 3***). The individual miscorrection scores were averaged across the individual trials in each condition to provide data for analysis. This process was carried out for TMS and no-TMS trials to assess miscorrection for both stimulation conditions. Trials in which the participants grasped the tool in the incorrect orientation for use were not included in the calculation of baseline performance or in the assessment of TMS trials, as this was deemed to be an incorrect reach. The percentage of these trials were analysed as error rate (% of total trials in condition).

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1.1.6.2. *Movement Time (MT)*

The onset of movement was defined as the time of button release, and completion of grasp was determined by the maximum forward movement of the hand (grasp completion). Movement times (MT) were examined between these time points.

1.1.6.3. *Percentage of movement time to peak velocity (TPV%)*

TPV% was calculated as the percentage of movement time at which maximum movement velocity (cm/s) occurred between movement onset and final grasp completion. This parameter was used to determine the percentage of movement at which slowing occurred.

1.2. Results

All data from experiment 1 are displayed in **Supplementary Table 1,** however, for the purpose of relevance, only findings pertaining to TMS will be discussed here. For a summary of the ANOVA, see **Supplementary Table 2**.

1.2.1. *Miscorrection scores*

Data analysis revealed a significant effect of TMS ($F_{(1, 19)} = 37.1, p < .001$) with increased miscorrection when rotating the hand to grasp the tool appropriately for use during TMS trials *(M±SD miscorrection score = 0.39±0.12)* compared to no-TMS trials *(M±SD miscorrection score = 0.23±0.02,* ***Fig.*** **4**), indicating that TMS over the SMG impedes correction to appropriate grasp orientation for familiar tools, consistent with our hypothesis. However, neither the main effect of Hemisphere of SMG stimulation ($F_{(1, 19)} = 0.1, p = .75$), nor the interaction between Hemisphere of SMG stimulation and TMS was present ($F_{(1, 19)} = 0.05, p = .82$), which fails to support the hypothesis of a left hemisphere bias for this function. No other significant interactions or effects were observed in miscorrection scores (for a summary of ANOVA see **Supplementary Table 2**).

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1.2.2. *Movement Time and % Time to Peak Velocity (TPV%)*

An effect of TMS consistent with our hypothesis was also observed in movement time ($F_{(1, 19)} = 7.5, p = .01$); TMS *(M±SD = 786±215ms)* increased overall movement time compared to no-TMS trials *(M±SD = 768±221ms)*. Furthermore, an effect of

Hemisphere of SMG stimulation *($F_{(1, 19)} = 4.8$, $p = .04$)* was also observed, with increased movement time for right *(M±SD = 810±228ms)* compared to left SMG stimulation *(M±SD = 744±226ms).* However, no interaction between TMS and Hemisphere of SMG simulation was found *($F_{(1, 19)} = 1.0$, $p = .32$).*

Percentage of time to peak velocity (TPV %) showed a significant effect of TMS *($F_{(1, 19)} = 4.6$, $p = .04$),* with lower TPV% for TMS trials *(M±SD = 31.0±10.0%)* compared to no-TMS trials *(M±SD = 32.7±10.4%).* This partially reflects the findings in movement times, in that TMS over the SMG caused an earlier TPV%, indicating a longer period of deceleration in approaching the target. However, no significant interaction between TMS and Hemisphere of SMG Stimulation was found *($F_{(1, 19)} = 0.06$, $p = .79$)*. In summary, SMG stimulation affected movement time, velocity and selection of appropriate grasp. However, our findings failed to support our hypothesis of left lateralisation.

1.3. Discussion

The increase in miscorrection scores, movement time and longer period of deceleration during reach for SMG stimulation implicate this region as important for the selection of appropriate orientation of grasp when reaching for tools for use. Furthermore, due to the rapid online correction necessary in the experiment, this implies a dynamic role of the SMG in monitoring action plans and in compensating for rapid changes in goal-oriented actions pertaining to the appropriate grasp orientation for use. Research discussed earlier (Tunik et al., 2008) implicates a role of the SMG in planning stages, prior to movement execution, but not in monitoring the execution of movement. Our findings do not conflict with this conclusion, but further imply that when changes in the plan are necessary the SMG plays a role in compensating for the changes to maintain the initial action plan. This observed effect could arguably be due to a role of the SMG in integrating conceptual knowledge, pertaining to a tool's use, into a suitable action plan for grasp; with TMS over the SMG delaying the integration of this conceptual input into the motor transformations for correction. This finding is consistent with proposals that objects that are to be acted with are mediated by the ventro-dorsal pathway (Brandi et al., 2014; Rizzolatti & Matelli, 2003; Vingerhoets, 2014) and that the SMG may monitor goal relevant hand orientation over the course of reaching.

Despite the significant effect of TMS over SMG, results showed this was not modulated by hemisphere. This conflicts with the left lateralisation of tool related activation observed in the literature (Johnson-Frey et al., 2005; Orban & Caruana, 2014; Peeters et al., 2013; Vingerhoets, 2014) suggesting a bilateral role of the SMG in performing online correction of actions when reaching for tools (when reaching with the left hand). Bilateral SMG activation for planning and execution of tool use gestures (Johnson-Frey et al., 2005) and appropriate grasping (Przybylski & Kroliczak, 2017) has previously been reported in imaging studies. While left SMG activation is observable during planning and execution of tool use gestures, right SMG is only activated during action execution. This suggests that the right SMG may serve a function pertaining to action execution that does not inherently involve the retrieval of tool knowledge, focusing instead on the spatial demands of the task. Furthermore, in a recent review of TMS based manipulation judgement tasks in the context of tool use theories, Lesourd et al (2017), posited that stimulation over the

SMG may have inhibitory effects on surrounding regions that are in anatomical proximity to the SMG, but with distinct functions from the SMG (Lesourd et al., 2017). In the case of right SMG stimulation here, the effects of TMS may have extended to the right IPS, being functionally responsible for extraction of object affordances and facilitating grasp (Buccino et al., 2004). The resulting delays to correction of grasp orientation may, therefore, be based on processing the affordances and spatial demands rather than tool related input. Online control of grasp behaviour is associated with the contralateral aIPS (Rice et al., 2007; Tunik et al., 2005) which provides a possible interpretation of our right SMG stimulation findings when reaching with the left hand, if we assume overlap between SMG and aIPS stimulation. However, it is difficult to dissociate the differing roles of the left and right SMG with the present data set. To address this question, we performed Experiment 2. We wanted to control for the possibility that the observed effects of right hemisphere stimulation in experiment 1 were due to similar contralateral effects pertaining to spatial or grasping functions that might facilitate tool use, while not involving tool specific knowledge. We hypothesised that the same effects would be observed for the left hand and left SMG stimulation that were present in experiment 1. We also predicted that effect would be smaller, if present, in the right hand right SMG stimulation condition.

2. Experiment 2

2.1. Methods

Experiment 2 used the same apparatus and procedure as experiment 1 with the following changes.

2.1.1. *Participants*

13 healthy right-handed participants (8 male, 5 female, age range 22 – 33, M±SD = 25.4±3.50 years) took part. 3 subjects had taken part in experiment 1 however, there was a gap of at least 4 weeks between experiments for each subject. Participants were identified as having a predominantly right-hand preference, with an average laterality quotient of 0.67 (SD = 0.23 range 0.55-1.0, Oldfield, 1971). One participant was removed from analysis due to errors in motion tracking (see Experiment 1 – participants 1.1.1.) during testing.

2.1.2 *Design*

A repeated measures design was used with one independent variable combining hemisphere of SMG stimulation and hand used for reaching (left/left or right/right). The 3 other independent variables were as in Experiment 1. Participants completed 64 trials, 8 per rotation condition per block, across 2 blocks of trials, one for each hemisphere of stimulation (fewer trials were implemented for brevity of testing). In contrast to experiment 1, participants performed the task with their right hand in one block, and their left in the other. Ipsilateral stimulation and reaching was used in order to establish if the ipsilateral effects of SMG stimulation observed in experiment 1 were observable for the right hemisphere and hand also (Left SMG, Left Hand vs. Right SMG, Right Hand, order counterbalanced between subjects).

2.2. Results

Data from experiment 2 were examined using the same methods as experiment 1 (**Supplementary Table 3** summarises the findings). Miscorrection scores, movement time (MT), and percentage of time to peak velocity were examined for left and right hand reaching with ipsilateral SMG stimulation. As with experiment 1, only findings pertaining to TMS will be discussed here. For a summary of the ANOVA results, see **Supplementary Table 4**.

2.2.1. *Miscorrection Scores*

Analysis revealed a significant effect of TMS on miscorrection scores ($F_{(1, 11)} = 52.9$, $p < .001$), with higher miscorrection in TMS trials ($M \pm SD = 0.45 \pm 0.11$) compared to no-TMS trials ($M \pm SD = 0.20 \pm 0.02$) (see ***Fig. 5***). This is consistent with our hypothesis, however, no main effect of Hemisphere of SMG stimulation ($F_{(1, 11)} = 0.7$, $p = .39$), or interaction between Hemisphere of SMG stimulation and TMS was present ($F_{(1, 11)} = 1.5$, $p = .24$). This finding that TMS over the SMG causes a deficit in selection of appropriate grasp is consistent with our hypothesis, however, the lack of left hemisphere bias fails to support previous models.

-------------------------------INSERT FIG. 5 around here-------------------------------

A significant TMS x Grasp x Congruence interaction was observed ($F_{(1, 11)} = 8.1$, $p = .01$). For non-TMS upright trials, congruent ($M \pm SD = 0.18 \pm 0.07$) and incongruent ($M \pm SD = 0.18 \pm 0.05$) miscorrection scores were similar, however, for inverted trials, congruent miscorrection scores ($M \pm SD = 0.23 \pm 0.03$) were higher than incongruent

(M±SD = 0.21±0.03). For TMS upright trials, congruent *(M±SD = 0.25±0.18)* miscorrection was much lower than incongruent *(M±SD = 0.48±0.31)*, while for TMS inverted trials, congruent *(M±SD = 0.61±0.25)* miscorrection was much higher than incongruent *(M±SD = 0.46±0.28)*. To examine this interaction further, subsequent 2 x 2 ANOVAs were carried out for the TMS and no-TMS results. For TMS data a significant Grasp x Congruence interaction was found ($F_{(1, 11)} = 5.2$, $p = .04$); however, this interaction was not observed in the no-TMS condition ($F_{(1, 11)} = 0.1$, $p = .72$), see ***Fig.* 6**.

-------------------------------INSERT FIG. 6 around here--------------------------------

2.2.2. *Movement Time and % Time to Peak Velocity (TPV %)*

No significant main effects of TMS ($F_{(1, 11)} = 2.5$, $p = .14$) or Hemisphere of stimulation ($F_{(1, 11)} = 2.8$, $p = .12$) were observed for movement time and no significant interaction between Hemisphere x TMS was observed ($F_{(1, 11)} = 0.09$, $p = .76$). For TPV%, no significant main effects of TMS ($F_{(1, 11)} = 0.4$, $p = .51$) or Hemisphere of stimulation ($F_{(1, 11)} = 3.8$, $p = .07$) were observed, and the interaction between Hemisphere x TMS was also not significant ($F_{(1, 11)} = 0.004$, $p = .94$).

2.3. <u>Discussion</u>

The findings from experiment 2 further highlight a role of the SMG in the selection of appropriate grasp orientation when reaching for tools for use when an online perturbation forces a correction of orientation. As with experiment 1, these results are consistent with the ventro-dorsal specificity for objects to be acted with; and our hypothesis that the SMG monitors goal relevant action plans during reaching toward tools for use. However, no effect of TMS was observed for increasing movement time or TPV%, inconsistent with our hypothesis and the results of experiment 1. Furthermore, there was no effect or interaction with Hemisphere of SMG stimulation for any of the kinematic measures. This indicates an absence of left hemisphere bias and a bilateral role of the SMG in selecting and monitoring an appropriate grasp orientation when reaching for familiar tools, based on the effect of SMG stimulation ipsilateral to the effector hand for both left and right hemisphere.

This effect was not unexpected provided the results from experiment 1 and previous findings of bilateral activation of the SMG for grasp execution of tools, independent of hand used (Przybylski & Kroliczak, 2017). These results also indicate that the effects of right SMG stimulation are unlikely to be accounted for by stimulation of neighbouring regions close to the right SMG when reaching with the contralateral hand (a possible interpretation we discussed in Experiment 1, section 1.4.); due to similar effects for correction delay with the ipsilateral hand, observable in experiment 2. This raises questions regarding whether the role of the SMG in this process is tool specific, and what potential role the right SMG fulfils also. We address these questions below.

3. General Discussion

In our task the target tool was perturbed in orientation, forcing participants to correct their grasp. Double-pulse TMS to the SMG delayed this correction of grasp orientation. TMS over the contralateral and ipsilateral SMG disrupted this process when reaching with the left hand, in experiment 1. This finding is consistent with a role of the left SMG in the online integration of information pertaining to tools into an appropriate action plan for use (Vingerhoets, 2014). Although the results cannot provide direct insight into the nature of this conceptual information (whether reasoning or manipulation based (Osiurak & Badets, 2016), the results do indicate that the goal oriented plan is monitored throughout action during reaching to allow compensation in the event of a necessary online correction. This finding is also consistent, however, with a role of the SMG in goal oriented planning and selection of appropriate action (Brandi et al., 2014; Tunik et al., 2008).

Furthermore, a recent meta-analysis of tool use literature (Reynaud et al., 2016) highlighted the importance of the left SMG in not only understanding relationships between hand and tool, but also between tool and target object. This function is essential to selection of appropriate grasp when planning actions (Buxbaum, 2017; Lesourd et al., 2017; Osiurak & Badets, 2016), indicating a more integral role of the left SMG over the right. Our findings are consistent to an extent with prominent tool use models (Buxbaum, 2017; Osiurak & Badets, 2016, 2017), but differ in terms of the timing and duration of SMG function in generating the action plan. In line with the ideomotor principle (Greenwald, 1970; Hommel, Musseler, Aschersleben, & Prinz, 2001; Massen & Prinz, 2007; Prinz, 1997), current models posit that tool knowledge is integral to generating the action plan for functional grasp and use, but that the actual execution is mediated by motor control structures independent of conceptual input pertaining to tool use. In this case the SMG would be redundant during execution as the action plan has already been generated prior to action, therefore TMS over the SMG should not disrupt execution. However, in the present experiments, due to perturbation of the tool's orientation, integration of tool knowledge is required to correct grasp orientation for functional use. As appropriate grasp orientation is integral to effectively use the tool, following grasp, this should require input from the SMG pertaining to knowledge (Buxbaum, 2017) or reasoning about the tool's functional property (Osiurak & Badets, 2017). This does not necessarily mean that information about the tool needs to be retrieved again (following the planning of action) or that a simulation of action must be generated 'de novo' due to changes in the object orientation. Rather, we posit that the SMG maintains aspects of the action plan that are functionally associated with *use* throughout the duration between motion onset and grasp completion (such as relationships between hand and tool, and between tool and target object) to select appropriate grasp based on the goal of action (Buxbaum, Kyle, Grossman, & Coslett, 2007; Lesourd et al., 2017; Reynaud et al., 2016). Following object perturbation, the SMG dynamically integrates this maintained representation with visuomotor information to facilitate goal oriented rapid online correction.

How can the lack of left lateralisation observed in our findings, coupled with the effects observed for right hand reaching with stimulation of the ipsilateral SMG, be interpreted? One conceivable explanation would be that the right SMG (compared with left SMG) serves an equally important role in selection of grasp orientation of tools for use. From this explanation, it would follow that the right SMG is a locus of tool knowledge integration into bilateral visuomotor transformations for use, conflicting with current models of the tool use network (Buxbaum et al., 2007; Kroliczak & Frey, 2009; Lesourd et al., 2017; Orban & Caruana, 2014; Peeters et al., 2009, 2013; Przybylski & Kroliczak, 2017). There are a number of reasons why this explanation is unsatisfactory. Firstly, although right SMG activation has previously been observed during execution of tool related actions (Johnson-Frey et al., 2005) and effector-independent actual grasping (Przybylski & Kroliczak, 2017), the left SMG is active during execution *and* planning (Brandi et al., 2014; Orban & Caruana, 2014; Reynaud et al., 2016); implicating a left bias for *understanding* of tool use gestures. Secondly, the left SMG shows stronger lateralised connectivity with the ipsilateral pMTG compared to the right SMG and pMTG, a region associated with stored semantic representations considered important in the planning of tool use actions (Ramayya et al., 2010). Thirdly, although cases have been reported of right hemisphere damage resulting in apraxia (Marchetti & Della Sala, 1997; Raymer et al., 1999), these are not comparable in number to those following left hemispheric damage (Sunderland et al., 2013) and not relatable to the right SMG deficits observed here. Furthermore, recent imaging data highlights a left hemisphere activation bias for grasping inclusive of wrist rotation to achieve a functional grasp (Przybylski & Kroliczak, 2017).

A more likely explanation of right SMG findings can be derived by examining the task requirements. With some notable exceptions (Brandi et al., 2014) many studies highlighting left lateralisation of function pertaining to tools require no physical visuomotor control towards tools during testing. Instead, the studies focus on planning and preparing gestures associated with tools, or on concepts pertaining to tools rather than initiation of action (Chao & Martin, 2000; Decety & Grèzes, 2001; Kellenbach et al., 2003; Martin, Wiggs, Ungerleider, & Haxby, 1996; Okada et al., 2000). In our experiments, grasping tools for the purpose of *use* was explicitly instructed and corresponding target objects on which to demonstrate tool actions were present. This, coupled with the rapid movement and online correction, could indicate that the processes being examined may pertain to the conceptual aspects of tools; however, the additional demands of the task may require supplementary processing without specificity for tools and recruitment of the right SMG.

Given the extent of neuroimaging and neuropsychological bias towards a left lateralisation of tool function, we consider the possibility that the right SMG is functionally distinct while still involved in the execution of the task. Structures of the right IPL have been associated with detection of salient events in the environment (Clark, Fannon, Lai, Benson, & Bauer, 2000; Gur et al., 2007; Kiehl et al., 2005; Kiehl, Laurens, Duty, Forster, & Liddle, 2001; Lagopoulos, Gordon, & Ward, 2006; Singh-Curry & Husain, 2009) and sustaining attention on goal oriented tasks (Adler et al., 2001; Häger et al., 1998; Johannsen et al., 1997; Singh-Curry & Husain, 2009; Vandenberghe, Gitelman, Parrish, & Mesulam, 2001). It could be argued that the right SMG serves functions pertaining to interactions with tools, but which are not tool specific. For example, controlling for spatial perturbations in the environment and adjusting to these demands, such as the rapid online correction during the task. Our findings in miscorrection are consistent, to some extent, with the deficits shown by patients with right IPL damage, which has been linked to severe disruption of spatial functions such as keeping track of object locations, and being aware of rapid changes in location (Mannan et al., 2005; Parton et al., 2006; Pisella, Berberovic, & Mattingley, 2004). The observed right SMG effect may be due to the disruption of these functions in relation to tracking the rapid rotation of the target tool, without specifically relating to conceptual aspects of the tool itself.

However, this still does not fully account for the bilateral effect observed for both ipsilateral and contralateral stimulation in left and right hand reaching. As discussed, we posit that the left and right SMG may serve different functions pertaining to tool use, but experimental dissociation of these functions needs further studies with additional control conditions. Firstly, a task including trials without tool rotation would address the difference in function suggested for the left and right SMG. As evidence suggests the right IPL is associated with tracking spatial changes (Clark et al., 2000; Gur et al., 2007; Kiehl et al., 2001; Singh-Curry & Husain, 2009) in the environment, this function should not be recruited when no online correction of movement is necessary; relying instead on the tool knowledge function of the left SMG. Secondly, TMS stimulation to control sites of parietal regions distinct from the SMG would achieve spatial specificity for the observed delays to correction, ensuring the role of the SMG pertains to tool related aspects of action rather than spatial demands of the task. Additionally, recent research implicates the importance of sub-divisions within the SMG, indicating that some areas are specialised for mechanical knowledge (area PF) while others serve to integrate this mechanical knowledge into action production systems to generate a mental simulation of action (aSMG) (Lesourd et al., 2017; Reynaud et al., 2016) and process affordances of objects in relation to grip size and location (IPS) (Przybylski & Kroliczak, 2017; Tunik et al., 2005). Further experiments should consider these divisions of function in the SMG using tasks and stimuli that selectively require understanding of mechanical function (Badets & Osiurak, 2015) (such as a judgement task between the properties of two objects in relation to one another); compared with tasks that require prediction of grasp, independent of mechanical function knowledge (Andres, Pelgrims, & Olivier, 2013). Selective disruption of sub-regions of the SMG is difficult (Ishibashi, Lambon Ralph, Saito, &

Pobric, 2011), requiring functional imaging with specific hypothesis testing for sub-regions (Lesourd et al., 2017). Dissociation of these functions would provide insights into the functional organisation of the IPL in regard to tool use and have wide reaching implications into the conceptual input required to execute tool use behaviour.

Our experiments cannot account for the nature of conceptual input that forms the basis of the previously posited maintained action plan followed during action execution (Osiurak & Badets, 2016). Further experiments that dissociate between whether technical reasoning (Osiurak & Badets, 2017) or reliance on stored semantic representations of use (Buxbaum, 2017), are necessary to understand this input. Follow-up experiments, closely linked to the current paradigm, could explore this through having participants reach for novel tools vs familiar tools to explore whether the left SMG has an inherent bias for familiar objects. This could be further developed to vary the intention of action (Tunik et al., 2008), between use and transport to assess whether transport of objects can be carried out independent of tool or mechanical understanding

In conclusion, this study revealed a role of the SMG in mediating goal-oriented actions and shows that the SMG has a dynamic online role in the selection of appropriate grasp during reaching and grasping of tools for use.

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Figures

Figure 1. Panels **A.-B.** describe an **upright incongruent** trial; rotation of the hand to correct grasp for tool in initial position (**A**.) is incongruent with orientation of hand for correct grasp of the target tool following perturbation (**B.**). Panel **C.** describes the 4 rotation conditions used. **1.** and **2.** indicate the start and end position of tools, **arrows** indicate direction of perturbation for each condition.

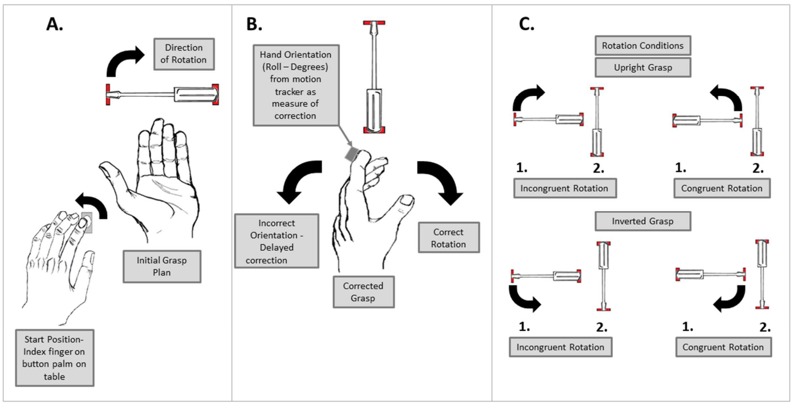
Figure 2. Average, estimated timeline for an example trial; for an inverted grasp with a congruent rotation; rotation of the hand to grasp for tool in initial position (**A**.) is congruent with rotation of hand for correct grasp of the target tool following perturbation (**B.)**. Movement and velocity data measured from **Reach Onset** to **Grasp Completion.** Hand orientation data analysed from **Tool Rotation** to **Grasp Completion** (shaded area of timeline – see **Fig. 3**).

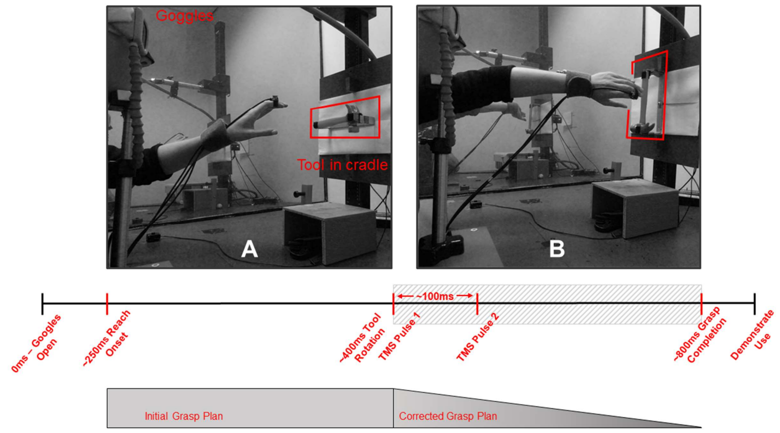
Figure 3. Reach pattern observed in hand rotation (Roll) in degrees for inverted incongruent trials sampled from 1 subject. Baseline represents averaged Roll across (no-TMS) trials. Sample **TMS trials (A and B)** illustrate method of miscorrection calculation. Points during trial that fall within **Baseline ±1 SD threshold** are assigned a zero value. The difference between **TMS trial** points external to threshold in the incorrect direction **(circled)** and **Baseline ±1 SD threshold** is measured as a multiple of standard deviation from the corresponding time point from the averaged **Baseline**. This creates a vector of zeroes (inside **±1 SD threshold**) and SD values (outside **±1 SD threshold**). The mean of this vector provides the **Miscorrection Score** for each trial. The individual **Miscorrection Scores** are used for analysis for each of the stimulation and rotation conditions.

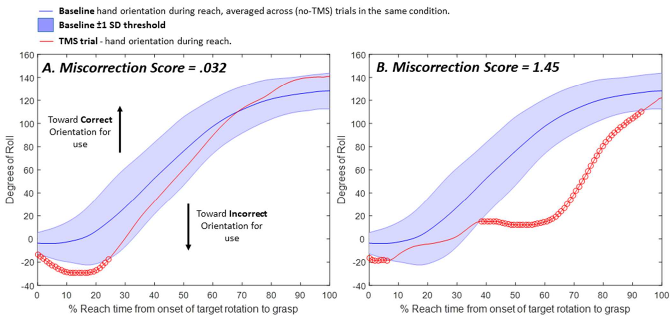
Figure 4. Experiment 1. Significant effect of TMS on miscorrection scores (SD) for contralateral and ipsilateral SMG stimulation while reaching with the left hand. Bars indicate ±1 SE of the mean miscorrection score across subjects, **($F_{(1, 19)} = 37.1$, $p <.001$).*

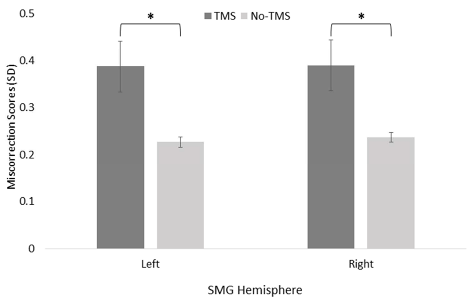
Figure 5. Experiment 2. Significant effect of TMS on miscorrection scores (SD) for stimulation of the SMG ipsilateral to the hand used for reaching (left and right). Bars indicate ±1 SE of the mean miscorrection score across subjects, *($F_{(1, 11)} = 52.9$, $p < .001$).

Figure 6. Experiment 2. Miscorrection Scores, TMS x Grasp x Congruence interaction. Bars indicate ±1 SE of the mean miscorrection score across subjects, *($F_{(1, 11)} = 8.1$, $p = .01$).*

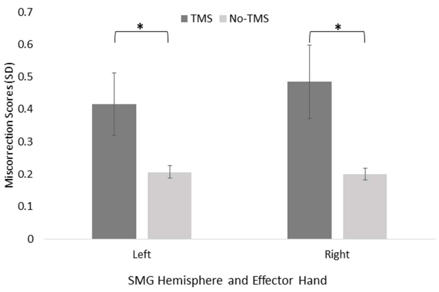

A.
Direction of Rotation
Initial Grasp Plan
Start Position- Index finger on button palm on table
B.
Hand Orientation (Roll – Degrees) from motion tracker as measure of correction
Incorrect Orientation - Delayed correction
Correct Rotation
Corrected Grasp
C.
Rotation Conditions
Upright Grasp
1.
2.
Incongruent Rotation
1.
2.
Congruent Rotation
Inverted Grasp
1.
2.
Incongruent Rotation
1.
2.
Congruent Rotation

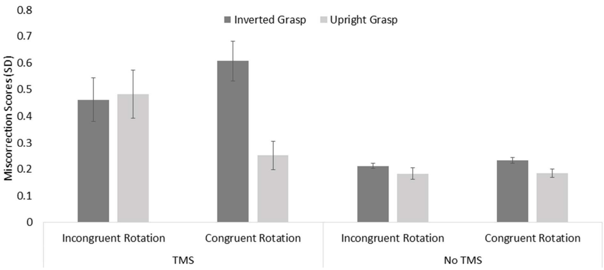

Goggles
Tool in cradle
A
B
~100ms
0ms – Googles Open
~250ms Reach Onset
~400ms Tool Rotation
TMS Pulse 1
TMS Pulse 2
~800ms Grasp Completion
Demonstrate Use
Initial Grasp Plan
Corrected Grasp Plan


Baseline hand orientation during reach, averaged across (no-TMS) trials in the same condition.
Baseline ±1 SD threshold
TMS trial - hand orientation during reach.
A. Miscorrection Score = .032
Toward Correct Orientation for use
Toward Incorrect Orientation for use
B. Miscorrection Score = 1.45
Degrees of Roll
% Reach time from onset of target rotation to grasp



0.5
0.4
0.3
0.2
0.1
0
Miscorrection Scores (SD)
TMS
No-TMS
*
*
Left
Right
SMG Hemisphere


TMS
No-TMS
Miscorrection Scores (SD)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
*
*
Left
Right
SMG Hemisphere and Effector Hand



0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Miscorrection Scores (SD)
Inverted Grasp
Upright Grasp
Incongruent Rotation
Congruent Rotation
Incongruent Rotation
Congruent Rotation
TMS
No TMS

Supplementary Materials

Supplementary Table 1. Experiment 1; Summary of mean data across stimulation and tool rotation conditions. M (±SD).

Hemisphere of Stimulation	TMS	Rotation Condition	MT(ms)	%TPV	Miscorrection Scores	Errors (%)
Left SMG	**TMS**	**II**	828 (276)	26.92 (8.43)	0.38 (0.34)	6.25 (9.06)
		IC	773 (230)	30.71 (12.29)	0.42 (0.29)	4.37 (7.33)
		UI	722 (218)	33.34 (11.01)	0.33 (0.25)	7.50 (17.33)
		UC	675 (208)	33.40 (11.63)	0.42 (0.51)	5.00 (8.51)
	no-TMS	**II**	793 (272)	29.59 (9.81)	0.23 (0.04)	8.12 (17.33)
		IC	766 (238)	30.79 (11.87)	0.24 (0.04)	5.00 (8.51)
		UI	717 (215)	35.23 (12.73)	0.22 (0.06)	6.88 (11.81)
		UC	675 (214)	34.78 (11.69)	0.22 (0.07)	3.12 (5.55)
Right SMG	**TMS**	**II**	897 (246)	28.67 (10.33)	0.46 (0.31)	2.50 (4.71)
		IC	846 (230)	30.13 (10.32)	0.32 (0.31)	3.75 (5.88)
		UI	733 (223)	33.21 (11.61)	0.35 (0.37)	6.25 (12.50)
		UC	772 (214)	32.08 (12.45)	0.43 (0.33)	2.50 (5.13)
	no-TMS	**II**	871 (252)	29.62 (10.98)	0.24 (0.04)	7.50 (13.08)
		IC	822 (247)	31.73 (11.04)	0.24 (0.05)	1.87 (6.12)
		UI	749 (229)	35.618 (14.03)	0.22 (0.08)	4.37 (10.16)
		UC	749 (224)	34.35 (11.72)	0.25 (0.01)	1.25 (3.85)

Mean movement times (MT) from button release to maximum forward movement towards target, % of reach time to peak velocity of movement (%TPV), Miscorrection scores (SD – see ***Fig.* 3**), and Error Rates (% of total trials in condition for grasping in the incorrect orientation) for each stimulation condition and corresponding no-TMS conditions. Rotation conditions, **II:** Inverted Incongruent, **IC:** Inverted Incongruent, **UI:** Upright Incongruent, **UC:** Upright Congruent.

Supplementary Materials

Supplementary Table 2. Experiment 1. Summary of repeated measures ANOVA - Hemisphere of SMG Stimulation x TMS x Grasp x Congruence (2 x 2 x 2 x 2) ANOVA: carried out for movement time (MT), % of time to peak velocity (%TPV) and miscorrection scores.

	MT(ms)		%TPV		Miscorrection Scores	
	F(1,19)	p	F(1,19)	P	F(1,19)	p
Hemisphere	**4.88**	**.04**	.004	.94	.10	.75
TMS	**7.51**	**.01**	**4.64**	**.04**	**37.17**	**<.0001**
Grasp	**73.40**	**<.001**	**31.36**	**<.001**	.17	.70
Congruence	**11.85**	**.003**	1.99	.17	.23	.63
Hemisphere x TMS	1.03	.32	.06	.79	.05	.82
Hemisphere x Grasp	.063	.80	.80	.38	.05	.81
TMS x Grasp	1.66	.21	.28	.60	.003	.95
Hemisphere x TMS x Grasp	.81	.37	.22	.63	.01	.90
Hemisphere x Congruence	2.65	.12	.91	.35	.95	.34
TMS x Congruence	.90	.35	.19	.66	.01	.91
Hemisphere x TMS x Congruence	.86	.36	1.00	.32	1.13	.30
Grasp x Congruence	2.72	.11	**8.97**	**.007**	1.37	.25
Hemisphere x Grasp x Congruence	3.65	.07	.016	.90	.94	.34
TMS x Grasp x Congruence	.39	.53	.10	.74	1.01	.32
Hemisphere x TMS x Grasp x Congruence	.28	.60	.47	.49	.29	.59

Supplementary Materials

Supplementary Table 3. Experiment 2; Summary of mean data across stimulation and tool rotation conditions. M (±SD).

Effector Hand	Hemisphere of Stimulation	TMS	Rotation Condition	MT(ms)	%TPV	Miscorrection Scores	Error Rates (%)
Left Hand	**Left SMG**	**TMS**	**II**	871 (250)	17.18 (3.81)	0.41 (0.31)	11.45 (22.27)
			IC	785 (190)	21.81 (7.15)	0.51 (0.36)	7.29 (14.55)
			UI	707 (186)	26.16 (11.22)	0.44 (0.35)	3.12 (5.65)
			UC	659 (209)	25.42 (10.81)	0.30 (0.29)	3.12 (5.65)
		no-TMS	**II**	805 (257)	19.26 (10.91)	0.19 (0.04)	11.45 (21.62)
			IC	753 (212)	22.07 (8.78)	0.23 (0.06)	15.62 (14.22)
			UI	682 (250)	30.17 (14.01)	0.19 (0.08)	6.25 (11.30)
			UC	674 (220)	23.46 (9.12)	0.20 (0.08)	4.16 (6.15)
Right Hand	**Right SMG**	**TMS**	**II**	989 (265)	27.97 (12.86)	0.51 (0.51)	9.37 (15.19)
			IC	828 (269)	32.24 (14.43)	0.69 (0.39)	9.37 (16.96)
			UI	811 (286)	33.38 (14.39)	0.52 (0.48)	21.87 (22.69)
			UC	792 (253)	35.52 (13.86)	0.19 (0.08)	13.54 (17.23)
		no-TMS	**II**	932 (304)	29.93 (11.52)	0.22 (0.04)	10.41 (15.84)
			IC	815 (330)	33.53 (16.39)	0.22 (0.04)	8.33 (18.71)
			UI	802 (371)	35.59 (14.41)	0.17 (0.09)	27.08 (29.59)
			UC	734 (295)	34.03 (15.69)	0.16 (0.08)	21.87 (20.03)

Mean movement times (MT) from button release to maximum forward movement towards target, % of reach time to peak velocity of movement (%TPV), Miscorrection scores (SD – see ***Fig.* 3**), and Error Rates (% of total trials in condition for grasping in the incorrect orientation) for each stimulation condition and corresponding no-TMS conditions. Rotation conditions, **II:** Inverted Incongruent, **IC:** Inverted Incongruent, **UI:** Upright Incongruent, **UC:** Upright Congruent.

Supplementary Materials

Supplementary Table 4. Experiment 2. Summary of repeated measures ANOVA - Hemisphere of SMG Stimulation x TMS x Grasp x Congruence (2 x 2 x 2 x 2) ANOVA: carried out for movement time (MT), % of time to peak velocity (%TPV) and miscorrection scores.

	MT(ms)		%TPV		Miscorrection Scores	
	$F_{(1,11)}$	p	$F_{(1,11)}$	p	$F_{(1,11)}$	p
Hemisphere	2.82	.12	3.81	.07	.77	.39
TMS	2.47	.14	.45	.51	**52.91**	**<.001**
Grasp	**58.49**	**<.001**	**19.39**	**.001**	**5.78**	**.03**
Congruence	**13.44**	**.004**	.93	.35	.13	.72
Hemisphere x TMS	.09	.76	.004	.94	1.50	.24
Hemisphere x Grasp	.18	.67	1.68	.22	1.06	.32
TMS x Grasp	.55	.47	.23	.63	1.98	.18
Hemisphere x TMS x Grasp	.32	.58	.39	.54	.33	.57
Hemisphere x Congruence	4.17	.06	1.41	.25	.35	.56
TMS x Congruence	.27	.61	2.42	.14	.38	.55
Hemisphere x TMS x Congruence	.59	.45	.24	.62	.04	.82
Grasp x Congruence	4.39	.06	**9.78**	**.01**	**11.34**	**.006**
Hemisphere x Grasp x Congruence	1.06	.32	1.37	.26	.77	.39
TMS x Grasp x Congruence	1.47	.25	1.27	.28	**8.19**	**.01**
Hemisphere x TMS x Grasp x Congruence	.71	.41	.02	.87	1.01	.33