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Citation: Vukovic, Nikola, Feurra, Matteo, Shpektor, Anna, Myachykov, Andriy and Shtyrov, Yury (2017) Primary motor cortex functionally contributes to language comprehension: An online rTMS study. *Neuropsychologia*, 96. pp. 222-229. ISSN 0028-3932

Published by: Elsevier

URL: <http://dx.doi.org/10.1016/j.neuropsychologia.2017....>
<<http://dx.doi.org/10.1016/j.neuropsychologia.2017.01.025>>

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Primary motor cortex functionally contributes to language comprehension: an online rTMS study

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ABSTRACT:

Among various questions pertinent to grounding human cognitive functions in a neurobiological substrate, the association between language and motor brain structures is a particularly debated one in neuroscience and psychology. While many studies support a broadly distributed model of language and semantics grounded, among other things, in the general modality-specific systems, theories disagree as to whether motor and sensory cortex activity observed during language processing is functional or epiphenomenal. Here, we assessed the role of motor areas in linguistic processing by investigating the responses of 28 healthy volunteers to different word types in semantic and lexical decision tasks, following repetitive transcranial magnetic stimulation (rTMS) of primary motor cortex. We found that early rTMS (delivered within 200 ms of word onset) produces a left-lateralised and meaning-specific change in reaction speed, slowing down behavioural responses to action-related words, and facilitating abstract words – an effect present only during semantic, but not lexical, decision. We interpret these data in light of action-perception theory of language, bolstering the claim that motor cortical areas play a functional role in language comprehension.

INTRODUCTION

The centrality of language in mediating socio-cultural and economic interactions, as well as the devastating impact on quality of life which follows impairments of the complex language-processing system, strongly underscore the importance of studying its neurophysiological foundations. Investigations of mechanisms underpinning the comprehension of meaning (i.e., semantics), have been a focus of neuroscience, linguistics, and psychology for decades. Nevertheless, the complex details relating to where and how semantics is processed and represented in the brain remain to be fully elucidated. The traditional model, borne out of early aphasiology research, functionally locates language in a network comprised of inferior frontal and superior temporal areas of the left hemisphere, with the former in charge of speech production and grammatical processing, and the latter subserving comprehension and perception of language (Geschwind 1970; Ojemann 1991). However, subsequent neuroimaging studies have drawn into question this model by showing that linguistic - and in particular semantic - processing appears to be linked to activation of neural circuits outside of the “core system” including what has always been considered as modality-specific areas (such as motor, auditory, or visual cortices; see e.g., Binder & Desai 2011; Boulenger et al. 2012; Meteyard et al. 2010). There are two broad ways in which researchers have attempted to reconcile the classical understanding with these brain and behavioural data (Barsalou 2008; Glenberg and Gallese 2011). One strand argues that activity outside the left perisylvian areas is epiphenomenal to language understanding, and reflects purely correlational, downstream activity, not necessary for efficient extraction of meaning from linguistic input (Mahon and Caramazza 2008). Others,

however, have proposed that language has an additional basis in modality-specific areas, particularly sensorimotor ones, and that the functional contribution of these areas becomes readily apparent when we look at comprehension of specific semantic categories (Pulvermüller 2011). Thus, there is presently a lack of consensus in the literature regarding the involvement of sensorimotor areas in language comprehension, highlighting the need for additional research. In particular, a distributed view of language faculty in the brain necessitates understanding whether and how activity in these areas might support comprehension of different aspects of word meaning.

The putative association between language and extra-sylvian modality-specific brain structures can be addressed by looking at the motor cortex, not least because of its distinctive neuronal activity profile and its somatotopic layout. For example, fMRI studies have shown that reading action words such as “run”, “punch” or “kiss” leads to increased blood flow to brain areas selectively controlling leg, arm and mouth movements, respectively (Hauk et al. 2004). Moreover, electrophysiological (electro- and magnetoencephalography, EEG/MEG) studies demonstrate that this motor activity increases extremely fast: For instance, the rholandic mu rhythm in the alpha and lower beta range, a characteristic signature of the motor system status, desynchronises within 200 ms from seeing action words in the subject’s first and even second language (Vukovic and Shtyrov 2014), and motor-related evoked EEG/MEG responses dissociate between semantic categories within 80-200 ms after the visual onset or spoken word recognition point (Hauk & Pulvermüller 2004; Shtyrov et al. 2014; however, see a discussion of the effect timing in commentaries by Papeo and Caramazza 2014, and Shtyrov and Stroganova 2015). These and similar findings provide support to an "action-perception" model of language, which posits that comprehension consists of partial re-activation of networks formed and used during immersed, real-world learning and experience, and grounds word meaning in distributed

cortical circuits comprised (in addition to core language areas) of the same perceptual and motor structures that support action and perception (Barsalou 2010). As such, this approach does not consider extra-sylvian brain areas as "peripheral" to language, but as functionally involved in encoding and subsequently representing modality-specific aspects of word meaning.

While many studies support this broadly distributed model of language and semantics, there are many others that argue that motor cortex activity observed in studies such as those above can be reconciled with classical models after all. The main argument proposed by critics of the action-perception model is that such activity may arise as a downstream by-product of language processing, and is therefore functionally "redundant" and irrelevant to the efficient meaning comprehension (Lotto et al. 2009; Mahon & Caramazza 2008). Indeed, some theorists rightly point out that available neuroimaging results provide largely *correlational, not causal* evidence for sensorimotor cortices' involvement in representing meaning. The claim of somatotopic mapping of action word semantics in the motor cortex has also been questioned. For example, Postle et al. (2008) have found increased fMRI activity in areas adjacent to motor cortex, which was correlated to generic action words, but there was no strong evidence of somatotopic organisation of this activation for words relating to effectors. The authors concluded that what is so far missing, but required, to support a motor theory of action semantics is "a demonstration that lesions to discrete motor areas have deleterious effects on the *understanding* of action words" (Postle et al. 2008). In conclusion, current literature contains contrasting accounts - to assess these contradictory claims and ascertain whether the motor system *functionally* contributes to language processing, we need experimental methodologies which allow for *causal inferencing*.

Transcranial magnetic stimulation (TMS) is a neurostimulation and neuromodulatory technique which allows the experimenter to directly interfere with ongoing activity in a local

patch of cortical neural tissue. Depending on stimulation parameters, TMS may induce a variety of changes in cortical excitability (Walsh and Rushworth 1998). It is generally agreed that trains of repetitive TMS (rTMS) may be delivered at a specific intensity and frequency to transiently disrupt the function of a target area, the so-called “virtual lesion” approach (Pascual-Leone et al. 2000). The non-invasiveness, reversibility, and temporal precision of TMS application make it a great tool for investigating functional interactions and changes in motor cortex during language processing.

Surprisingly, very few studies to date have directly assessed online modality-specific semantic processing in the brain using TMS. Some studies have used indirect measures, such as motor-evoked muscle potentials (MEPs) elicited by TMS during a behavioural task. For instance, Buccino et al. (2005) found that listening to action-related sentences specifically suppresses the TMS-elicited hand- and foot-muscle MEPs, while Gianelli and Dalla Volta (2015) showed that passive viewing of hand-related verbs leads to an amplitude increase in MEPs recorded from hand muscles. Papeo et al. (2014) showed that MEPs to action verbs were larger than for non-action verbs, but this difference was not significant after repetitive TMS (rTMS) to superior temporal areas, leading the authors to conclude that only the latter are “true” carriers of semantic information, cognitively mediating activity arising in motor cortices. Thus, there are conflicting experimental findings in the literature, with confusion compounded by the fact that the influence of TMS on motor cortex during verb processing was mostly assessed using MEPs, and not directly through language performance as such. Note that motor-evoked potentials merely reflect the status of the motor system and do not provide any causal evidence about a semantic role of motor cortex in comprehension: They only show that linguistic processing affects the excitability of the motor cortex, which could in principle be a downstream and a semantically shallow effect. To show the reverse, namely, that motor cortex stimulation influences language processing, one

must measure direct behavioural effects of motor-system TMS on linguistic performance.

The latter was attempted in even fewer studies. In their seminal study, Pulvermüller et al. (2005) measured reaction times (RTs) in a lexical decision task (LDT) using a single pulse TMS protocol and demonstrated a somatotopy-specific improvement/facilitation in behavioural performance. Similar patterns were shown in Willems et al. (2011), who also employed a lexical decision task, and, unlike previous studies, stimulated premotor areas, rather than the primary motor cortex. While these studies show a facilitative effect of TMS stimulation on action word processing, and thus suggest some motor cortex involvement in language, they still do not provide direct evidence that sensorimotor cortical interference can *disrupt* semantic processing, which would be necessary to support a causal role for these areas in language comprehension. Moreover, these studies used a semantically relatively shallow task – lexical decision. While there is abundant evidence that (aspects of) meaning become activated spontaneously in a variety of language tasks (Dilkina et al. 2010; Lagrou et al. 2011, 2012; Vukovic and Williams 2014; Yap et al. 2015), judging whether a string of letters is familiar or not *per se* does not *require* deep semantic processing, particularly not of motor semantic features - see Barsalou et al. (2008) for evidence of shallower meaning access in these and similar tasks, as well as Solomon and Barsalou (2004) and Kan et al. (2003). An approach is therefore needed, which would explicitly control for linguistic performance by using tasks requiring variable activation of semantic features, including motor ones. A TMS study which compared performance in multiple behavioural tasks was conducted by Tomasino et al. (2008), whose participants performed a silent reading task, a visual imagery task, and a frequency judgement task (how often a word appears in newspapers). The authors found that TMS did not influence performance in spontaneous linguistic processing, unlike during explicit imagery, where stimulation of hand primary-motor (M1) cortex facilitated responses. However, similarly to above, it can be argued

that these experimental tasks do not explicitly require full retrieval of meaning – which is particularly true for judging how frequently a word appears in newspapers (a task which is highly unusual, and in fact led to average response latencies around 1200 ms - twice as long as is typical in language tasks; for example, see Faust 2012).

In conclusion, although direct causal evidence for the role of motor cortex in processing of action-semantic aspects of meaning would be highly important in delineating neurobiological mechanisms of language comprehension, it is surprisingly scarce in the TMS literature. Further, to substantiate or refute the claims of sensorimotor semantics, it is essential to test whether any *disruptive* influence of motor cortex stimulation could occur *during* linguistic processing, requiring studies using an *online* TMS approach, as opposed to offline stimulation research (Repetto et al. 2013; Willems et al. 2011).

CURRENT STUDY

The present study was aimed at addressing the causal role of motor areas in linguistic processing, contrasting performance in concreteness judgement tasks and lexical decision tasks. As was already noted, Motor Evoked Potentials (similarly to EEG or fMRI) allow only correlational inferencing; therefore, our study directly measured behavioural outcomes, i.e., reaction times in linguistic tasks as the dependent variable. To assess effects of motor cortex stimulation on action word comprehension specifically, we contrasted performance in a concreteness judgement task and a lexical decision task. Critically, only the former of these, but not the latter, requires explicit access to motor components of action word meaning (here, those specifically related to manual actions). Finally, we used an online interference rTMS protocol with an early latency (within 200 ms from stimulus onset), in order to target online meaning processing, as opposed to post-comprehension activity (Marslen-Wilson and Tyler 1980). For

neuroanatomical precision, we used navigated rTMS based on individual subjects' structural magnetic-resonance images. Previous research has demonstrated robust left-hemispheric dominance for language in right-handers (Knecht et al. 2000), based on which we hypothesised that applying an online interference TMS protocol (20Hz burst of 4 pulses) over the left M1 hand area would cause a modulation of response times, leading to slower RTs to hand action words, but not to non-action words. Since the motor cortex is argued to support motoric components of word meaning specifically, we expected to see the (strongest) effect during the concreteness judgement task, as opposed to lexical decision, as only the former explicitly requires retrieval of action-semantic features. Right hemisphere M1 hand area was used as a control TMS site. We predicted no change in reaction times for this control area in right-handers, since previous fMRI research has shown it not to be involved in processing unimanual action words (Willems et al. 2010; Casasanto 2011). This site was confirmed to be suitable as a control based on earlier TMS studies showing that 20 Hz quadripulse protocols (i.e. 4 subthreshold pulses delivered with a gap of 50 ms) of M1 do not affect contralateral measures of active or resting motor threshold, short- or long-interval intracortical inhibition, or intracortical facilitation (Hamada and Ugawa 2010; Tsutsumi et al. 2014).

METHODS

Participants

We tested 28 right-handed (Oldfield 1971) native speakers of Russian. Of those, ten were male, and eighteen female. The participants' average age was 23.10 (SD = 3.64). All participants had normal or corrected-to-normal vision, no history of neurological or language disorders, and no counter indications to TMS (Rossi et al. 2009). Prior to testing, participants gave written informed consent, and were monetarily compensated for taking part in the study. The study

protocol conformed to the Declaration of Helsinki and was approved by the local University Research Ethics committee.

Stimuli and Task

To investigate processing differences in contexts that do or do not explicitly require access of motor semantic information, we used two visual experimental tasks: lexical decision *vs.* concreteness judgement. Each participant completed both tasks, and their order was pseudo-randomly interleaved in blocks during each testing session. The presentation of stimuli and response collection were handled by E-prime 2.0 Professional software (Psychology Software Tools, Inc., Pittsburgh, PA, USA). For the Lexical Decision Task (LDT), real Russian unimanual hand action words were used (e.g. “write”, “draw”; see Table 1 below for stimulus examples), as well as pseudo-words obeying Russian phonotactics and orthography. On each LDT trial, participants would see a central fixation cross for 500 ms, after which a (pseudo)word would appear for another 500 ms, followed by a 1000 ms inter-trial-interval (ITI, jittered between 900-1100 ms in 10 ms steps) during which a fixation cross was again present (Figure 1A). The participants' task was to press one of two response buttons, as quickly as possible, indicating whether the word was real or not. Failure to respond within the duration of a single trial (i.e. 1500 ms from word onset) would lead to presentation of a "Too Slow" feedback screen.

The Concreteness Judgement Task (CJT) used the identical trial structure as the LDT, but the words presented were either concrete words (action words, as in the LDT), or abstract words, unrelated to physical bodily activity (such as "think", "infer", "decide"). For this task, participants were instructed to quickly press one of two keys, indicating whether the word they saw was concrete or not. As such, this task was different from the LDT task mentioned above in that it necessitates a more comprehensive access to various aspects of word meaning, including

those purported to be supported by the motor cortex (i.e. action-semantic features).

Participants responded using the left or right hand, and the order was determined by rTMS stimulation protocol (described in detail below), such that the response hand was always ipsilateral to the stimulated hemisphere, in order to avoid any muscle twitches due to trans-synaptic activation of the corticospinal system (Volz et al. 2014).

The target stimuli used in the experiment consisted of 50 Russian action (hand-related, and thus concrete) words, 50 abstract words, and 50 matched pseudowords. All words were drawn from the Russian Internet Corpus (Sharoff 2005) and the pseudowords were produced by shuffling the syllables of real words, resulting in phonologically and orthographically plausible combinations. Each subject saw each target word in LDT and CJT tasks twice. Across subjects, stimuli were randomised in lists such that their order of presentation in the lexical and semantic/concreteness judgement task was counterbalanced. Action (i.e. concrete) and abstract words were controlled for a range of psycholinguistic features such as letter length, base and log lexical frequency, as well as semantic factors of action-relatedness and concreteness. Out of these, additional pseudowords were constructed through syllable shuffling so that they matched real words in length, bi- and tri-gram frequency. Table 1 contains a summary of stimuli and example items.

	Examples	NL	RIC Tokens	RIC Frequency
Action Words	рисуешь (draw-2SG-PROG) пишешь (write-2SG-PROG)	8.3 (1.87)	32.33 (39.70)	0.16 (0.19)
Abstract Words	веруешь (believe-2SG-PROG) простишь (forgive-2SG-PROG)	8.62 (1.86)	33.62 (33.30)	0.17 (0.16)
Pseudo Words	шмакишь белдешь	-	-	-

Table 1. Examples and frequency measures for target stimuli obtained from the Russian Internet Corpus (Sharoff, 2005; <http://corpus.leeds.ac.uk>) and Russian National Corpus (<http://ruscorpora.ru>). Number of letters, RIC Token number, RIC Word Frequency, with SD in parentheses. Word stimuli were all presented inflected for second person singular, present progressive.

TMS Protocol

During the testing session, participants were seated in a comfortable armchair, with their elbows flexed at a straight angle and hands pronated and relaxed. A headrest was used in order to maintain a comfortable head position. TMS stimulation was delivered using a 65-mm figure-of-eight coil, with the handle oriented posteriorly at 45° angle from the midline, and powered by a MagPro X100 stimulator (MagVenture, Inc., Atlanta, Georgia USA). Throughout, biphasic shaped pulses were used. The two stimulation sites were the left and right hemisphere M1 hand area. Each participant underwent both right and left hand M1 stimulation, and the order of stimulation between sites was pseudo-randomised across subjects. Exact stimulation coordinates were determined at an individual level using T1-weighted structural MRI scans (1.5T Inera Scanner, Philips Medical Systems, Best, Netherlands). To ensure stable and accurate positioning over each hotspot throughout the session, we used a Localite frameless stereotaxy system (TMS Navigator, Localite GmbH, Sankt Augustin, Germany) for co-registration and navigation. We determined each subject's resting Motor Threshold (rMT) individually for the left and right hemisphere, defined as the minimum intensity required to induce MEPs > 50µV (peak-to-peak) in the contralateral FDI muscle in at least 50% of trials. TMS intensity used during the experimental tasks was then fixed at 90% of the weighted average of left and right rMT.

For stimulation trials, rTMS was delivered at the onset of the word, and lasted for 200 ms. The frequency of stimulation was set at 20 Hz (i.e. 4 pulses were sent for every word, with 50-ms gaps between consecutive pulses), based on previous studies which on the one hand demonstrated local interference effects following this protocol and on the other hand excluded any inter-hemispheric effect (Hamada and Ugawa 2010; Tsutsumi et al. 2014; Gerloff et al. 1997; Rossi et al. 2002, 2006, 2011; Berent et al. 2015).

In addition to the left and right M1 TMS stimulation conditions, behavioural CJT and LDT data were collected for a baseline condition (for left and right hand responses), which was identical to those described above except that no TMS stimulation occurred.

Statistical analyses

Reaction times falling outside of the individual participant's Mean +/- 2SD range were not analysed (3.11% of the entire dataset was excluded in this fashion). TMS stimulation is known to produce separable local and general effects simultaneously, therefore to distinguish between specific and non-specific effects we followed the procedure described in Dräger et al. (2004): First, for each condition, we calculated average reaction time (RT) changes (Δ) at each stimulation site as a measure of local effects:

$$\Delta RT(x) = RT_{TMS(x)} - RT_{BASELINE},$$

following which we calculated the general TMS effect (ΔRT_{MEAN}) by looking at the average Δ value over all stimulation sites and conditions:

$$\Delta RT_{MEAN} = (\Delta RT(x) + \Delta RT(y))/2,$$

where x and y represent individual stimulation sites. In order to isolate the specific reaction time change at each stimulation site ($\Delta RT_{SPEC(x)}$), we subtracted the mean TMS effect from each site:

$$\Delta RT_{SPEC(x)} = \Delta RT(x) - \Delta RT_{MEAN}.$$

The resulting ΔRT_{SPEC} values reflected specific changes in the speed of response due to TMS stimulation (as opposed to non-specific effects of TMS-related attentional arousal, or pre-stimulation differences reflecting general effects of no present interest, such as the well-known finding that words are faster to respond to than non-words). These were entered into a 2x2x2 repeated measures ANOVA, with the independent factors of Task (LDT vs. CJT), Stimulation

Site (Left Motor vs. Right Motor), and Stimulus Type (Word vs. Pseudo-word in LDT, and Concrete vs. Abstract word in CJT). In addition, we performed the same ANOVA for the analysis of error rates. Significant interactions were followed up in separate analyses at all levels of interaction, and were Bonferroni-corrected for multiple comparisons.

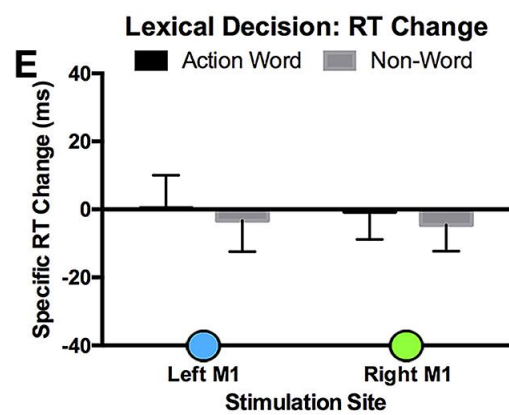
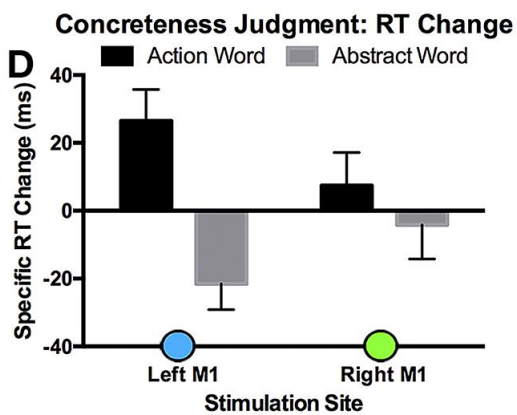
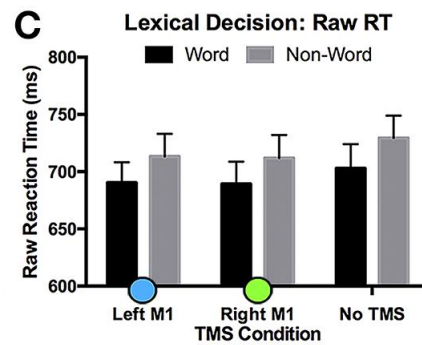
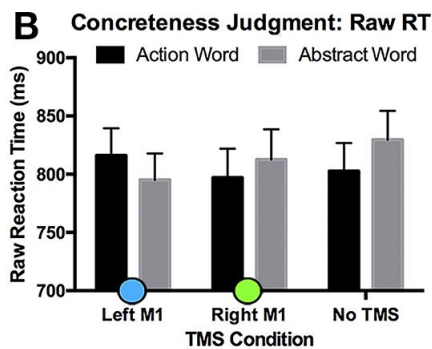
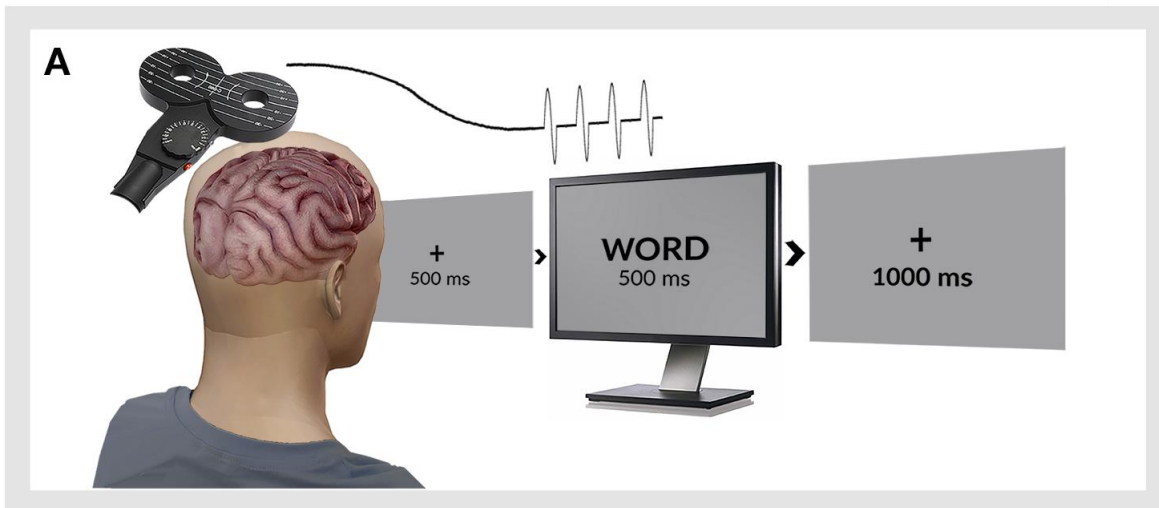


Figure 1. TMS stimulation, experiment trial structure, and behavioural results (RT, error bars indicate standard error of mean). (A) In each CJT/LDT trial, participants saw a fixation cross for 500 ms, followed by the word target for 500 ms, and again a fixation for 1 s. At word onset, 20 Hz repetitive TMS stimulation was administered (4 pulses separated by 50 ms), with intensity set at 90% resting motor threshold. (B-C) Raw RT values for CJT and LDT tasks, respectively. (D) Results showing specific RT changes from baseline (see Methods) indicate that TMS stimulation caused slower responses to action words, and faster responses to abstract words in the semantic judgment task, but only for left motor cortex stimulation. (E) Responses to action words and pseudowords during the lexical decision task did not differ after left or right M1 stimulation.

RESULTS

All participants successfully completed both tasks. The repeated measures ANOVA of error rates returned a significant main effect of Task [$F(1, 27) = 73.57$, $p < 0.001$, partial $\eta^2 = 0.732$]: as expected, participants made fewer errors on the easier task, i.e. lexical decision, with only 3.3% incorrect responses on average, as opposed to 9.1% of the trials involving concreteness judgements. No other main effects or interactions were significant in the error-rate analysis.

After accounting for the non-specific effect of TMS ($\Delta RT_{\text{MEAN}} = 12.92$ ms), specific RT changes for each site and condition were entered into a repeated measures ANOVA, which returned a significant main effect of Stimulus Type [$F(1, 27) = 8.47$, $p = 0.007$, partial $\eta^2 = 0.239$]. There was a two-way interaction between Stimulation Site and Stimulus Type [$F(1, 27) = 5.62$, $p = 0.025$, partial $\eta^2 = 0.172$] which was, in turn, qualified by a significant three-way interaction between Task, Stimulation Site, and Stimulus Type [$F(1, 27) = 6.57$, $p = 0.016$, partial $\eta^2 = 0.196$]. We therefore followed up this interaction with two ANOVAs for LDT and CJT tasks separately, each with the factor of Stimulation Site and Stimulus Type.

The results of these follow-up analyses were remarkably different between the lexical decision and semantic (i.e. concreteness) judgement task. Whereas the ANOVA did not return

any significant main effects or interactions for the LDT RT values ($p > 0.05$), analysis of reaction time changes in CJT returned a significant main effect of Stimulus Type [i.e., concrete action vs. abstract semantics; $F(1, 27) = 14.65$, $p = 0.001$, partial $\eta^2 = 0.352$]. Crucially, for the CJT task only, we found a two-way interaction between the factors of Stimulus Type (action vs abstract semantics) and Stimulation Site (left vs right motor cortex hand area) [$F(1, 27) = 7.94$, $p = 0.009$, partial $\eta^2 = 0.227$]. Investigating this interaction, a two-tailed two-sample t-test did not indicate any significant differences between responses following Right M1 stimulation (Figure 1E), whereas the responses following Left M1 stimulation differed significantly [$t(27) = 6.06$, $p < .001$], indicating a specific RT slowdown of 26.48 ms when responding to Action words, compared to a 21.55 ms relative facilitation when evaluating Abstract words (see Figure 1D.). Where relevant, we confirmed that the sphericity assumption was not violated using Mauchley's test ($p > 0.05$).

DISCUSSION

We set out to test functional contributions of the primary motor cortex in language tasks which do or do not require access to action-semantic features using an MR-navigated online rTMS protocol. Analysis of the specific reaction time changes in our study revealed that early (within 200 ms) disruption of the motor cortex hand representation during word processing led to hemisphere-, task-, and meaning-specific changes in the speed of behavioural responses. Significant effects were only observed following left hemisphere stimulation, which agrees with previous research showing a strong left-hemispheric dominance for language function in right-handed individuals (Knecht et al. 2000). Moreover, we found that rTMS did not change the speed of processing in those linguistic contexts, as in the LDT task here, where a more elaborate access to motoric aspects of word meaning is not a task requirement. However, when we asked

participants to judge verbs semantically – specifically, to evaluate their concreteness, thus requiring more in-depth processing of motor components of meaning – rTMS stimulation of the left (but not right) motor cortex led to the registration of slower responses to hand action words, and faster responses to abstract words.

Theoretically, the causal character of the present effect (*slower* semantic processing of action related words after TMS) suggests that the role of the motor cortex in comprehension is inherently functional, and that this involvement is evident when processing *semantic action-related* aspects of language. Our methodology allowed us to interfere with regular motor cortex functioning and thereby observe causal consequences of this neural perturbation on word processing. Since stimulation only occurred within the first 200 ms of word onset, it would appear that TMS disrupted early stages of lexico-semantic analysis, as opposed to post-comprehension imagery, though a definitive chronometry of these effects remains to be examined (e.g., via a combined TMS and EEG approach).

What mechanism can explain the observed causal role of motor cortex in action language processing? We believe that our data can be most easily reconciled with - and are in fact predicted by - the simulation theory of semantics (Barsalou 2010). According to this view, when we read or hear a word, we access its meaning, at least in part, by mentally simulating the perceptual, motor, affective, and other information associated with the corresponding meaning. At a neural level, the simulation consists of partially reactivating the same brain networks which were involved during learning and subsequent re-use of the word *in its referential context*. In other words, in order to access the word's meaning, one has to “re-experience” its activation history. For example, understanding the verb “punch” would involve using the motor cortex to simulate the kind of motor programs needed to actually perform the action of punching. In accordance with this logic, if we disrupt the neural tissue coding aspects of word meaning, we

should expect to see delays in processing - the effect we observed in our study for hand action words after TMS stimulation of the left M1 hand area. From this perspective, an increase in reaction times to hand-action words following left motor hand area TMS is a result of an incomplete and, therefore, suboptimal activation of a word representation, leading to a longer processing time.

It is important to note, however, that it would be *unwarranted* to claim that *motor cortex alone* is both *necessary and sufficient* for understanding language. Such a claim would conflict with the classical literature on language neuroarchitecture. Whereas it is noteworthy that motor cortex dysfunction does seem to lead to word processing difficulties, such as in Motor Neuron Disease and inferior-frontal lesions (Bak et al. 2001; Bak and Hodges 2003; Boulenger et al. 2008; Cotelli et al. 2006; Tranel et al. 2003); there is also patient data where a link between motor lesions and action language seems to be absent (Kemmerer et al. 2012; Kalénine et al. 2009; Arevalo et al. 2012; Papeo et al. 2010). More generally, postulating exclusive reliance on any one modal brain area would not be warranted by most theoretical approaches, including the simulation theory. Instead, the lexical-semantic representation of any word is best conceptualised as a neural circuit broadly distributed over (multiple) modality-specific as well as higher-level multimodal areas. For example, a simple action word bundles together aspects from the auditory (how the word or even the action sounds), motor (how the referent action is performed), visual (how the activity looks from different perspectives), affective (positive or negative emotion, associated for example with motor proficiency), somatosensory (what does it feel like to perform an action), articulatory (the word production algorithm) and other modal and supra-modal areas. Individual experiences, such as one's language learning context and history, also influence the extent to which distributed multimodal circuits are recruited in word processing. For example, handedness influences whether left or right motor cortex becomes active during action word

processing (Willems et al. 2010), proficiency in first or second language influences the extent of such activation (Vukovic and Shtyrov 2014), as does professional and motoric experience, such as in experts vs. novices (Del et al. 2010; Behmer and Jantzen 2011). Learning context also plays a role, and activity in visual and motor cortices predicts superior performance even months after enriched (multi-sensory) word learning, but not if words are learned by passive reading or translation (Mayer et al. 2015). Finally, more research is needed on how TMS affects semantically shallow tasks, in which performance does not depend on conscious retrieval of word meaning. We find no evidence in our data that M1 TMS stimulation disrupted action word processing in the lexical decision task. Thus, while our protocol likely affected motoric components of action verb semantics (as suggested by responses in the concreteness judgement task), these representations are not required for evaluating the word's lexicality, thus leaving performance unaffected. It would be interesting, however, to see what effect motor TMS has on lexical judgments of other word categories, including abstract ones – a contrast which was not present in this study, since we only evaluated action- and pseudo-words in our lexical decision task. While this limitation of our study (related to limits on rTMS experiment duration) warrants further investigations, this matter has been to a degree addressed by previous studies, which showed that TMS stimulation of premotor and motor cortices does not affect response times during lexical decision for abstract verbs, and verbs referring to intellectual and symbolic activities (Willems et al. 2011; Repetto et al. 2013).

It is also worth noting that TMS has been shown to induce both local and network effects (Eldaief et al. 2011; Shafi et al. 2012). On the basis of present data, it is impossible to exclude the possibility that our protocol induced activity in neighbouring premotor or prefrontal areas, known to be part of the linguistic system more broadly. Indeed, cortico-cortical disinhibition of adjacent network nodes, caused by interference with primary motor cortex, may account for the

observed facilitation of abstract verb responses in our semantic task, since abstract verb processing has previously been linked to prefrontal brain activity (Cappa et al. 2002; Binder et al. 2005, 2009; Sakreida et al. 2013; Borghi and Zarcone 2016). Facilitation in responses due to release from intracortical inhibition is a well-known phenomenon, and made possible by the fact that brain systems operate in concert, balanced by mutual inhibitory and facilitative mechanisms through inter- and intracortical connections. Perhaps the most dramatic demonstration of these mechanisms are the many clinical studies where patients with dysfunctions or neural damage in one part of the cortex show improved behavioural performance in certain cognitive tasks, compared to their pre-lesioned state, or even to normal controls (Kapur 1996; Najib, Umer Pascual-Leone 2011; Kapur et al. 2013). Delivering interference TMS protocols to a target region could thus cause a functional disinhibition (and hence facilitative effects on behaviour) of structures connected to the said region and relevant for the behavioural task at hand (see Moliadze et al. 2003; Dräger et al. 2004; for examples where TMS protocols can cause bidirectional parallel effects, both interfering with and facilitating processing). On a related note, responding in our semantic task required comparing concrete and abstract word features, where overlapping or competing representations arguably need to inhibit the dispreferred one (e.g., for primarily concrete verbs, inhibiting secondary abstract or idiomatic meanings), disrupting the left motor cortex with TMS may have facilitated processing of abstract words by removing/reducing non-preferred processing in a part of the language comprehension network. Such an explanation would be in line with neurobiological models of language based on sensorimotor circuits, where “mutual inhibition between overlapping assemblies could be realized by striatal connections, [with category-specific words] distributed assemblies sharing their perisylvian part while inhibiting each others [semantic parts] through striatal connections” (Pulvermüller 1999).

Whether the observed responses for abstract words are best explained by TMS-induced network effects, leading to facilitative activation of associated representations in nearby areas, or by removing the competition from M1-mediated concrete words, is a question which can be fruitfully answered by combining TMS, EEG and fMRI in future research. These issues notwithstanding, and crucially for our study's main hypothesis, it is clear from the distinct pattern of observed effects that disrupting the left M1, as part of the broader language network, appears to selectively *interfere* with semantic, as opposed to lexical, processing of action but not abstract verbs.

CONCLUSION

In conclusion, we found evidence that an early motor cortex-TMS interference protocol produces a left-lateralised, task-, and meaning-specific change in response latencies, slowing down processing of action-related words, compared to faster abstract word responses. We interpret these data in light of the action-perception theory of language comprehension, bolstering the claim that cortical areas supporting action play a functional role in language processing. Thus, the results strongly suggest causal involvement of modality-specific circuits in language comprehension, showing that even high-order cognitive phenomena are grounded in basic biological mechanisms.

ACKNOWLEDGEMENTS

This work was supported by Aarhus University (Denmark), Lundbeck Foundation (Denmark; NeoLex: R140- 2013-12951, project 15480), HSE Centre for Cognition and Decision Making (Moscow) and by the Russian Academic Excellence Programme '5-100'.

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