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Research article

Corticospinal excitability during the processing of handwritten and typed words and non-words

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HIGHLIGHTS

- TMS was applied to left primary motor cortex during observation of videos of handwritten and typed words and non-words.
- MEPs from the FDI muscle were measured.
- Facilitation of MEPs was observed for handwritten stimuli for both words and non-words.
- Facilitation was not observed for typed stimuli.
- Motor system plays a strong role in perception of written language.

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ABSTRACT

A number of studies have suggested that perception of actions is accompanied by motor simulation of those actions. To further explore this proposal, we applied Transcranial magnetic stimulation (TMS) to the left primary motor cortex during the observation of handwritten and typed language stimuli, including words and non-word consonant clusters. We recorded motor-evoked potentials (MEPs) from the right first dorsal interosseous (FDI) muscle to measure cortico-spinal excitability during written text perception. We observed a facilitation in MEPs for handwritten stimuli, regardless of whether the stimuli were words or non-words, suggesting potential motor simulation during observation. We did not observe a similar facilitation for the typed stimuli, suggesting that motor simulation was not occurring during observation of typed text. By demonstrating potential simulation of written language text during observation, these findings add to a growing literature suggesting that the motor system plays a strong role in the perception of written language.

1. Introduction

Language is a deeply embodied system. We speak using our tongue and mouth muscles, we write using our hands, and we learn the meanings of words by observing the sensory and motor features present while hearing those words. Understanding the role that motor activation plays in each context of language processing is an ongoing enterprise. Many processes considered to be a part of the motor system have been revealed to have involvement in language [1–4]. Several competing explanations exist as to why non-motor cognition and perception would call on the motor system, including simulation theories [5–8], active prediction theories [9–11], and motor resonance theories [12].

A large body of work has looked into understanding the relationship between the motor system and language use in humans [4,13–16]. One theory called the “motor theory of speech perception”, put forth by Liberman and Mattingly [17], proposed that speech perception entails mapping the acoustic patterns of sound onto the gestures that are used in their creation. Fadiga et al. [1] hypothesized that the mapping of these gestures involves mapping to their own respective motor system, in which case we should see activation of the mouth motor region of someone listening to speech. They applied single-pulse transcranial magnetic stimulation (TMS) to the cortical tongue region of participants as they passively listened to words with either a double “rr” phoneme or the double “ff” phoneme. Motor-evoked potentials (MEPs) measuring cortico-spinal excitability were obtained from the tongue muscle using electromyography (EMG). Higher MEPs were observed in the “rr” condition, whose pronunciation involves

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more movement of the tongue muscle, suggesting that participants were in fact using their own motor regions during speech perception. Skipper, Nusbaum, and Small [18] found that there was even greater increased motor activity while participants both saw and heard faces speaking, compared to only hearing or only seeing.

With the exception of Fadiga et al. and Skipper et al.'s findings, most of the research on the role of language in the motor cortex has focused on motor processing of *action-based* language, or the semantic content of language. Numerous studies, for example, provide evidence that action language, whether written or heard, and in words or full sentences, relies on the motor system for processing [14,15,19,20]. However, language is also created using the motor system. As Fadiga et al.'s findings demonstrate, hearing spoken language relies on the activation of the mouth region of the cortical motor system.

Written language has been less explored in the context of the motor system. We learn reading and writing using our sensorimotor system to write letters and words on paper or type them on a keyboard. A recent behavioral study by Beilock and Holt [21] found evidence that skilled typists may be simulating typed letters as they perceive them. They asked participants who were either expert or novice typists in an experiment to choose which of two competing letter dyads they liked better. Participants chose between a dyad of two letters that require the same finger using traditional typing methods [i.e., F, V] or a dyad of two letters that require different fingers using traditional typing methods [i.e., F, J]. They found that experts had a slight preference for the dyads that used different fingers to produce each letter, while novices did not exhibit a preference for either option. A motor task performed while making dyad preference judgments attenuated the preference of the skilled typists but only when the motor task involved the specific fingers that would be used to type the dyads. These findings suggest that in skilled typists, perceiving letters involves sensorimotor simulation of typing, which in turn influences affective judgments such as likeability.

In line with the abovementioned results, we designed an experiment to measure activation of the motor system during the perception of written language. For this purpose, we applied single-pulse TMS over left M1 and recorded MEPs from the right first dorsal interosseous (FDI) muscle in the right hand while participants saw words or non-words typed out or handwritten. We used only non-action words to avoid the recruitment of the motor system for the semantic component of action language. We predicted that during the appearance of typed or handwritten text, simulation of an inferred agent typing or writing would cause an increase in corticospinal excitability measured by MEPs. The motivation behind this experiment was twofold. The major aim was to extend theories of language embodiment to written language. We also aimed to further our understanding of the role of the motor system in non-motor processes such as language perception. While the present experiment was not aimed to distinguish between any existing theories of motor involvement, testing action observation in more and different contexts can add to this emerging area of research.

2. Methods

2.1. Participants

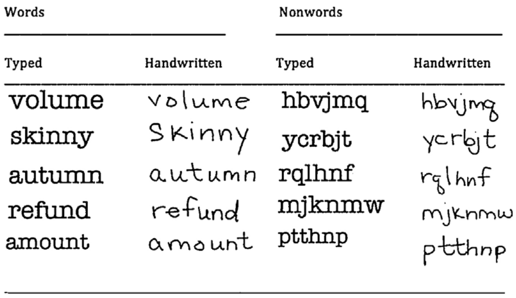
Twenty-four right-handed normal participants (8 males, 16 females, mean age ~19.5) were recruited in this study through UC Merced's SONA research system. All participants passed a safety screen and gave written, informed consent. The experimental procedure was approved by the UC Merced Institutional Review Board for research ethics. Participants received 2 research credits that can be used for credit in some undergraduate courses.

2.2. TMS and EMG recording

Corticospinal excitability was measured by the amplitude of motor evoked potentials (MEPs) recorded using electromyography (EMG) on the first dorsal interosseous (FDI) muscle of the right hand. MEPs were chosen as the primary measurement because we were targeting corticospinal excitability during passive observation while subjects rested their hand. Related measures also reported in the literature, such as cortical silent period or MEP recruitment curves, could provide a more detailed measure of corticospinal excitability. However, due to constraints on number of stimulations we wanted to apply to participants and the desire for passive observation, MEP amplitude was the optimal measure for our purposes. Two small adhesive electrodes (1cm$\hat{2}$) were placed over the belly of the recorded muscle and a ground electrode was placed over a bone on the participant's elbow. A bandpass filter (50 Hz–1000 Hz) was applied to the EMG signal, which was digitized at 1000 Hz for offline analysis. MEPs were elicited by applying single-pulse TMS to the FDI region of the left motor cortex. Pulses were delivered using a Magstim Rapid^2 ™ with an attached 70 mm figure-of-eight coil positioned over the optimal scalp location with the handle pointing backward at 45 ° from the midline. The procedure was as follows. Subjects were fitted with a swim cap that was covered by a grid of dots placed 1 cm^2 apart. Optimal scalp position was determined by moving the coil by one centimeter intervals until the location eliciting the best MEPs was identified. This location was marked on the swim cap worn by the participant. After determining the stimulation site, we relied on Visor™ (ANT-Neuro Enschede, Netherlands) – a motion capture based neuronavigation software to ensure that the coil does not move during the duration of the experiment. This method allows for accurate repositioning throughout the experimental sessions and is consistent with the standard methods used for stimulation of M1. Resting motor threshold was determined as the percent of machine output that produced 5 out of 10 MEPs of at least 50 μV peak-to-peak amplitude. The methods described here are very similar to our previous work involving stimulation of the primary motor cortex [25,26]. The stimulation intensity during the experiment was set to 120% of a participant's resting motor threshold. The coil was held steady at the optimal position throughout the experiment. Subjects were instructed to keep their head still and remain relaxed for the duration of the experiment.

2.3. Experimental paradigm

The visual stimuli consisted of videos of either handwritten or typed words or non-words appearing letter by letter at a variable presentation speed averaging 3–4 letters per second. Non-words in this experiment were groups of consonants. Words and non-words were the same length (between 6 and 8 letters). Words were chosen that did not relate to any actions or manipulable objects, to ensure that our measurement would not be influenced by the effects of semantic processing of action. We also included 10 baseline trials, which consisted of a single black box for the same duration as the stimuli. We chose to randomize the baseline trials in with the rest of the trials so that the baseline measure would not be biased by a lack of attention that can occur when baseline measures are all recorded pre-experiment. Stimuli included five words and five non-words, which appeared four times in each of the conditions. This resulted in 80 stimulus trials and 10 baseline trials, or a total of 90 trials. Eight seconds passed in between individual trials, and the total experiment length was approximately 12 min. Because TMS stimulation would occur two seconds into the video, we ensured that the typed stimuli would display one of the following letters at that time [N, H, U, M, J, I], so that if subjects were simulating the typing, FDI would be the simulating muscle.



Words		Nonwords	
Typed	Handwritten	Typed	Handwritten
volume	volume	hbvjmq	hbvjmq
skinny	Skinny	ycrbjt	ycrbjt
autumn	autumn	rqlhnf	rqlhnf
refund	refund	mjknmw	mjknmw
amount	amount	ptthnp	ptthnp

Fig. 1. Sample stimuli used in the experiment. The typed stimuli appeared letter by letter. The handwritten stimuli appeared as if written out continuously. Videos used in the experiment are included in supplementary materials.

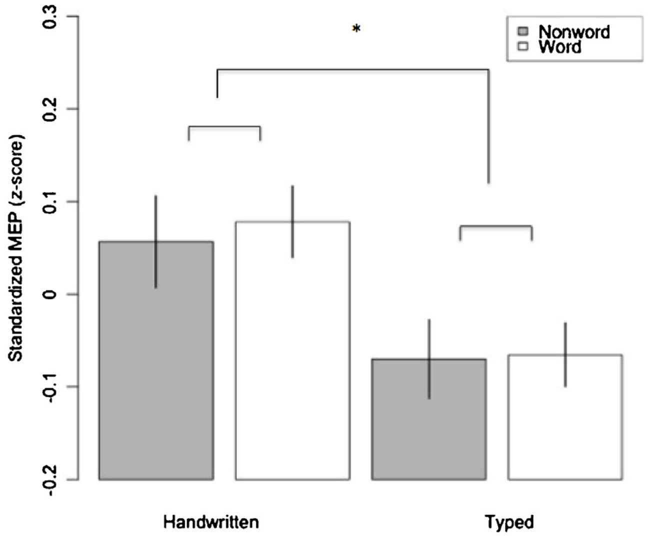


Fig. 2. Standardized (Z-scored) MEP amplitudes for each condition. Data from all subjects. Motor evoked potentials in the handwritten condition show facilitation. Vertical bars denote standard error means. Asterisks denote significant ($p < .05$) differences between conditions.

The stimuli appeared on a flat screen monitor placed in front of the participants. Participants were instructed to attend to the stimuli on the screen and were given notice when the experiment was one-third and two-thirds of the way finished to prevent loss of attention. Breaks were provided upon participant request. TMS pulses were delivered 2 s after video onset. The interval between trials was 8 s, to avoid any cumulative effects of single-pulse TMS. After the experiment, subjects were asked whether they were able to stay attentive during the length of the experiment. Participants who said they were not were excluded from analyses (5 subjects). The stimulus details are shown in Fig. 1 (please also see supplementary materials for video presentations).

3. Results

In order to use inter-individual comparisons, Z scores were calculated for each participant. Trials in which MEP amplitudes were larger than 2.5 standard deviations from the mean and those less than 50 μV were excluded as outliers. Less than 5% of all data were excluded. Statistical analyses were carried out in R. Repeated measures two-way analysis of variance (ANOVA) was conducted on the normalized data for condition (typed or handwritten) and stimulus type (word or non-word). Fig. 2 shows the average Z-scores for each of the conditions.

As seen in Fig. 2, we found a significant main effect of condition ($F(1,23) = 9.52$ $p < .01$), indicating that MEP amplitude was modulated by whether the stimuli were handwritten or typed. Specifically, the handwritten stimuli showed a much greater facilitation of MEPs than the typed stimuli.

The main effect for stimulus type (word or non-word) was not significant ($F(1,23) = .25$, $p > .6$), suggesting that motor cortex activation was not modulated by whether the stimulus was a real English word or a non-pronounceable consonant group. The interaction between condition and stimulus type also did not approach significance ($F(1,92) = .08$, $p > .7$), suggesting that the handwritten stimuli facilitation did not vary between words and non-words.

4. Discussion

In the present experiment, we found evidence for simulation of handwritten text during observation, regardless of whether the text segments were real words or groups of consonants. We did not, however, find evidence for simulation of typed text of the same nature. While the present experiment was not aimed to distinguish between any existing theories of motor involvement, testing action observation in more and different contexts can add to the evolving data that exists.

Here we show that passively observing handwritten words leads to an automatic facilitation of the reader's motor cortex. This automatic facilitation during reading perception is very similar to that found in Fadiga et al.'s speech perception experiment, where spoken stimuli involving greater tongue motion produce facilitation in MEPs recorded from the tongue muscle. An interesting difference in the present work is that if subjects are simulating an observed agent, in this case they must also infer an agent that is not present. In the case of our stimuli, this would mean that subjects are simulating the creation of the stimuli from a temporally-removed agent that previously created them. Evidence in favor of the simulation of inferred agents comes from some work in the action observation literature. Umiltà et al. [22] found, during single-cell recording, that some subset of neurons in the macaque fire during the final part of an observed action, even if that final part of the action is occluded from view. Importantly, this suggests that these neurons are simulating the action of an inferred agent when the actor is no longer in sight. Further evidence for this comes from work by Kohler and colleagues [23], where they were also recording from single neurons in monkey premotor cortex. They found that some of the same neurons that fire during a produced and observed action will also fire when monkeys are only hearing the auditory information from the action (i.e., the cracking of a peanut). When only hearing the action, subjects must be inferring an agent.

There are other potential explanations for modulation of MEPs in the handwritten stimuli. One possibility is that participants are simulating writing the stimuli themselves, without inference to another agent. An interesting follow up in this regard would be to observe how MEP amplitude changes if handwritten words appear in a participant's own handwriting, or if MEPs are measured on the *non-dominant* hand during TMS of the contralateral motor cortex. Another possibility is that the motor system is active in sensory prediction of the motion of the handwritten stimuli. More specifically, the motor system might be using something that Wilson and Knoblich [24] refer to as emulators, whereby perceptual prediction of the very next sensory state of a stimulus is being modeled using the motor system. While we might expect that we would see the same modulation in the typed stimuli if prediction were responsible, perhaps the one-by-one appearance of typed text does not evoke the same kind of sensorimotor prediction as the continuous fluid motion of the handwritten stimuli. In other words, perhaps any continuously developing line would lead to activation of the motor system, whereas the instantaneous nature of all-at-once letter appearance does not lead to this motor recruitment. Recent work by Schubotz [11] suggests that the motor system (premotor cortex in particular) is active during the perception of inanimate events, by showing that prediction of these events corresponds with activation in somatotopically-relevant areas of the premotor cortex. For instance, spatial prediction tasks lead to activation in regions of premotor cortex that typically share activation for executed/observed foot-related actions, whereas rhythm/pitch prediction tasks lead to activation in areas corresponding to executed/observed mouth actions. One way to explore this potential mechanism would be to measure corticospinal excitability during the appearance of a continuously developing line on screen and comparing to the presently obtained results.

Additionally, written language is learned in an embodied manner, learning letters and words via the process of using our motor system to create them. What our results suggest is that even the simple perceptual processes involved in reading handwritten language is embodying these learned motor reproductions of text. While it is interesting that this strong effect does not hold for the typewritten words, it is perhaps not that surprising. In a world where we read text from digital devices constantly, this connection between text and motor commands is not as direct and strong as that with handwritten language, except perhaps for expert typists [1]. As our society moves away from the use of handwriting and more toward text being produced primarily with technological means such as typing, though frequently with thumbs instead of fingers, it will be interesting to see whether this embodiment of language changes as a result.

On the methodological front, it would be of interest to measure modulation of corticospinal excitability using an active measure, such as cortical silent period (CSP), while subjects were actively contracting the relevant muscle, for instance by holding their hand in a position primed for handwriting. However, the large body of work in this area including work on action observation [1,12,13,18] use the MEP as the dependent measure for quantifying cortico-spinal excitability. More work is required to compare the relationship between active CSPs and MEPs in tasks such as the one we have used in this paper. It would also be useful to see how active motor threshold used in repetitive stimulation studies [25,26] can be used as a dependent measure during action observation experiments. While the behavioral responses make mapping motor cortical locations straightforward, methodological improvements can be made by using navigation based stimulation for recording MEPs [27].

Our results add to a growing body of literature suggesting that recruitment of the motor system is widespread, even in contexts with less obvious action-related perceptual information. Language in particular is a multimodal embodied system, showing reliance on the motor system for spoken language, written language, and the understanding of semantics. We also add to the evidence in favor of embodied simulation by introducing another instance of embodiment, whereby the perceptual-cognitive process of reading handwritten text involves motor simulation. Moving forward, it is important to observe how motor recruitment changes with changes in the environment. We see that handwritten stimuli involves motor simulation when the actual writing is observed, but what about during observation of static handwritten text that was created beforehand? Future directions for this work include exploring how repetitive stimulation of TMS to create virtual lesions over important sensorimotor regions modifies language perception and the recruitment of the motor system for language. Other work aims to measure the potential additive effect of simulation of written text and of action words to see if motor activation is higher when both of these forms of language embodiment are present.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.neulet.2017.05.021.

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