The Role of Primary Motor Cortex in

Second Language Word Recognition

by

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ABSTRACT

The activation of the primary motor cortex (M1) is common in speech perception tasks that involve difficult listening conditions. Although the challenge of recognizing and discriminating non-native speech sounds appears to be an instantiation of listening under difficult circumstances, it is still unknown if M1 recruitment is facilitatory of second language speech perception. The purpose of this study was to investigate the role of M1 associated with speech motor centers in processing acoustic inputs in the native (L1) and second language (L2), using repetitive Transcranial Magnetic Stimulation (rTMS) to selectively alter neural activity in M1. Thirty-six healthy English/Spanish bilingual subjects participated in the experiment. The performance on a listening word-to-picture matching task was measured before and after real- and sham-rTMS to the orbicularis oris (lip muscle) associated M1. Vowel Space Area (VSA) obtained from recordings of participants reading a passage in L2 before and after real-rTMS, was calculated to determine its utility as an rTMS aftereffect measure. There was high variability in the aftereffect of the rTMS protocol to the lip muscle among the participants. Approximately 50% of participants showed an inhibitory effect of rTMS, evidenced by smaller motor evoked potentials (MEPs) area, whereas the other 50% had a facilitatory effect, with larger MEPs. This suggests that rTMS has a complex influence on M1 excitability, and relying on grand-average results can obscure important individual differences in rTMS physiological and functional outcomes. Evidence of motor support to word recognition in the L2 was found. Participants showing an inhibitory aftereffect of rTMS on M1 produced slower and less accurate responses in the L2 task, whereas those showing a facilitatory aftereffect of rTMS on M1 produced more accurate responses in L2. In contrast, no effect of rTMS was found on the L1, where accuracy and speed were very similar after sham- and real-rTMS. The L2 VSA measure was indicative of the aftereffect of rTMS to M1 associated with speech production, supporting its utility as an rTMS aftereffect measure. This result revealed an interesting and novel relation between cerebral motor cortex activation and speech measures.

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Introduction

It is estimated that 50% of the world is bilingual; that is more than 3.5 billion people. In Europe, 54% of the population speaks at least two languages, 25% speaks three languages, and 10% four languages. Seventy-four percent of young people between 15 and 24 years of age are bilingual, and 37% of this population speaks at least three languages (European Commission, 2012). Although in the U.S. the number of bilinguals is not as impressive, the growth of the bilingual population during the last two decades is significant. In 1990 the percentage of U.S. population who spoke a language other than English at home was 13.8%. By the year 2000, it was 17.8%, and by the year 2013 more than 60 million people (21%) in the U.S. spoke a language other than English at home (U.S. Census Bureau, 2015). Being bilingual has become critical in this age of globalization where human communication needs to overcome language barriers. This growth in the bilingual and multilingual population in the world highlights the importance of research on the role of human neurobiology in shaping the bilingual linguistic capacity, and the neurophysiological processes involved in the comprehension of a second language (L2).

The ability to perceive novel non-native speech sounds is essential for L2 comprehension (Intartaglia et al., 2016; Kissling, 2015). However, the innate capacity to identify nonnative phonemic contrasts declines after the first year of life (Kuhl, 2010; Mattys, White, & Melhorn, 2005; Sebastián-Gallés & Soto-Faraco, 1999). Thereafter, perceptual distinction requires a series of increasingly slow and resource-intensive cognitive processes to identify contrasts and this negatively affects L2 word recognition (Burgaleta, Baus, Díaz, & Sebastián-Gallés, 2014). Nevertheless, proficient sequential bilinguals (those who learned L2 after the native language was already established) can reach optimal non-native speech comprehension; how this is accomplished has become a relevant question for theories of non-native speech processing.

This critical synergy between the sound production and sound perception systems in L2 learning is not specified. Current neurocognitive models suggest that the primary motor cortex (M1) plays a role in speech comprehension under difficult circumstances, for example when the speech signal undergoes external (environmental factors like noise) and/or internal (characteristics of the speaker like accent, style, or vocal tract differences) distortions (Adank, 2012; Devlin & Aydelott, 2009; Du, Buchsbaum, Grady, & Alain, 2014; Nuttall, Kennedy-Higgins, Hogan, Devlin, & Adank, 2016; Van Engen & Peelle, 2014). The challenge of recognizing and discriminating non-native speech sounds in L2 speech comprehension is regarded as an instantiation of “listening under difficult circumstances” and therefore is well suited to these recently developed neurocognitive models. In particular, the general prediction is that L2 processing recruits M1.

The purpose of this project was to investigate the role of speech motor centers, specifically the lip orbicularis oris (OO) muscle activity associated M1 in processing acoustic inputs in L2. In other words, is it important for the speech production system (muscle activity) to be recruited to enhance or augment the speech perceptual system? Repetitive Transcranial Magnetic Stimulation (rTMS) was used to selectively alter neural activity in lip M1 of English/Spanish bilingual speakers to examine the effect on word recognition. Thus, rTMS was used to interfere with the neural recruitment of M1. Additionally, a measure of subsequent speech production (vowel space area, VSA) following sham and rTMS was explored for aftereffects. This project seeks to gain insight into the human cognitive and neural mechanisms underlying the comprehension of L2 speech, contributes to the body of literature on neurophysiological processes involved in L2 acquisition and comprehension, and examines methodological implications of the use of rTMS for speech research. Specifically, this project aimed at answering 3 questions:

1. Does selective alteration of speech production M1 yield an interference in a word recognition task in comparison to a sham condition where M1 is not altered? Participants performed on a listening word-to-picture matching task before and after rTMS and sham-rTMS to the lip associated M1. This project tested the hypothesis that M1 is engaged during speech perception (Bartoli et al., 2013; D’Ausilio, Bufalari, Salmas, & Fadiga, 2012; Nuttall et al., 2016; Repetto, Colombo, Cipresso, & Riva, 2013). If M1 has a role in speech word recognition, longer reaction times and more errors were expected after rTMS compared to sham-rTMS to speech motor centers.

2. Does selective alteration of M1 yield more interference in a word recognition task in L2 compared to the native language (L1)? Participants performed on a L1 and L2 listening word-to-picture matching task, before and after rTMS stimulation to the lip associated M1. Differences in recognition performance between languages after a “virtual lesion” applied to M1 have important implications for theories on L2 processing. If M1 has a relevant role during speech recognition that requires greater cognitive effort and higher processing load as suggested by previous evidence (Abutalebi, Tettamanti, & Perani, 2009; Hernandez, 2009; Hernandez & Meschyan, 2006; Rodriguez-Fornells et al., 2005; Stasenko et al., 2015; Xue, Dong, Jin, & Zhang, 2004), longer reaction times and a larger number of errors in L2 word recognition compared to L1 were expected after rTMS to speech motor centers.

3. Is VSA an accurate measure of the aftereffect of low frequency rTMS on the lip associated M1? Changes in speech production characteristics have relevant methodological implications for the use of rTMS on language research. The modulatory effect on M1 produced by rTMS (Möttönen, Rogers, & Watkins, 2014; Möttönen & Watkins, 2012; Takenobu Murakami, Restle, & Ziemann, 2011; Takenobu Murakami, Ugawa, & Ziemann, 2013; Pascual-Leone, Walsh, & Rothwell, 2000), should be detected by differences in VSA between pre- and post-rTMS.

Theoretical Background

The scientific knowledge related the role of the primary motor cortex (M1) on language comprehension is having an important change due to research findings during the 21st century. The traditional models of language that separated perceptual and production modules in distinct brain regions, are being challenged by recent studies demonstrating that the motor cortex is engaged during speech perception (Bartoli et al., 2013; D'Ausilio, Craighero, & Fadiga, 2012; Fadiga, Craighero, Buccino, & Rizzolatti, 2002; Pulvermüller et al., 2006; Schmitz et al., 2018; Wilson, 2009), suggesting that speech perception and production rely partly on the same neural mechanisms (Möttönen & Watkins, 2009). The idea of motor processes being involved in speech perception is not new. The motor theory proposed by Liberman, Cooper, Shankweiler, and Studdert-Kennedy (1967) argued that the listener's motor representations are *necessary* for processing speech sounds, because "speech is perceived by reference to production". The difference with more recent neurocognitive models of speech perception (Figure 1), is the idea of motor processes having a *modulatory influence* on perception, but they are *not necessary* for speech comprehension (Hickok, 2015; Hickok, Holt, & Lotto, 2009; Lotto, Hickok, & Holt, 2009).

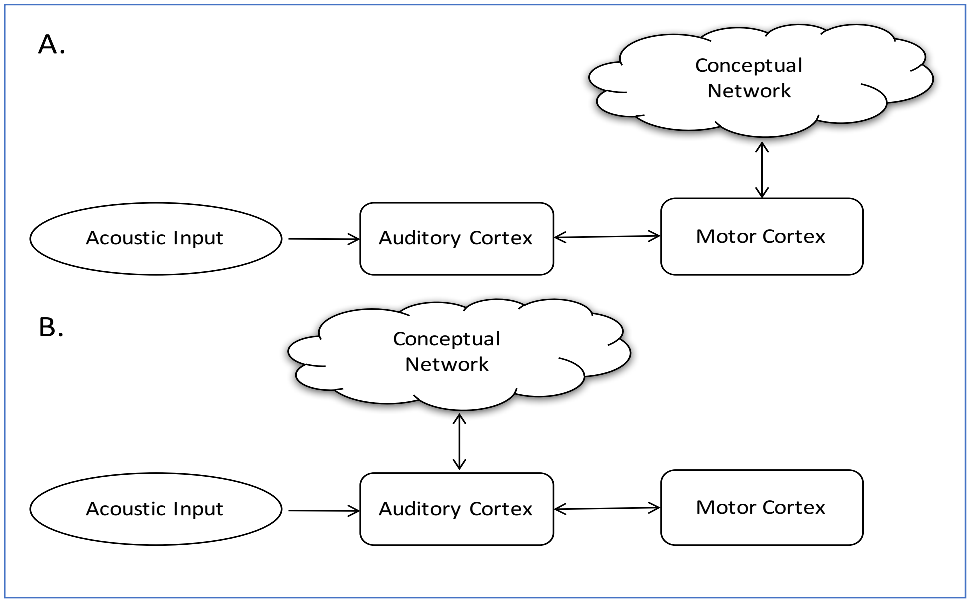

Figure 1. Schematic models of speech perception (adapted from Hickok, Holt & Lotto, 2009). A. Motor theory (Liberman et al., 1967). B. Neurocognitive models (Lotto et al., 2009, Hickok, 2015).

Empirical evidence is emerging showing that speech related motor areas are active while listening to verbal stimuli (D’Ausilio et al., 2009; Fadiga et al., 2002; Galantucci, Fowler, & Goldstein, 2009; Meister, Wilson, Deblieck, Wu, & Iacoboni, 2007; Repetto et al., 2013; Roy, Craighero, Fabbri-Destro, & Fadiga, 2008; Schomers, Kirilina, Weigand, Bajbouj, & Pulvermuller, 2015; Vukovic, Feurra, Shpektor, Myachykov, & Shtyrov, 2016; Wilson, Saygin, Sereno, & Iacoboni, 2004). These research supports the idea that motor articulatory representations are involved for optimal performance during speech processing. The motor system plays a significant role in speech perception because the speech input makes a connection with the motor system to support comprehension (Pulvermüller et al., 2006; Schomers et al., 2015; Wilson & Iacoboni, 2006). The acoustic and articulatory representations necessary for language production and comprehension are connected, and this association between representations implies that the motor system is also engaged during speech comprehension. For instance, Schomers et al. (2015) found that the articulatory motor cortex may have a casual effect on meaningful spoken word comprehension. They presented minimal pairs of words that started with a bilabial or an alveolar stop consonant in a word-to-picture- matching task, immediately after Transcranial Magnetic Stimulation (TMS) was applied to the left motor cortex either to the lip or the tongue area. It was found that response times were shorter and accuracy was higher when a congruent sector of the articulatory motor cortex (lip or tongue) was stimulated, in comparison to the stimulation of incongruous motor areas. Similarly, Cheung, Hamiton, Johnson, and Chang (2016) recorded direct neural activity from the peri-Sylvian speech cortex in participants undergoing clinical monitoring for epilepsy surgery. They found activation in the pre-central regions implicated in phonation and laryngeal control while listening to speech, suggesting that the motor cortex plays a role in speech perception. Willems, Labruna, D’Esposito, Ivry, and Casasanto (2011), found that lexical decisions for manual action verbs were faster after theta-burst stimulation (TBS) to the left premotor cortex in comparison to TBS to the right hemisphere, suggesting that processing action verbs is partly dependent on the activity of motor areas related to the planning and execution of the action named by the verb. Repetto et al. (2013), also found a facilitatory effect of M1 on semantic processing, confirmed by the fact that temporary disruption of the left M1 produced a delay in concrete action verbs processing.

In a functional magnetic resonance imaging (fMRI) study, Pulvermüller et al. (2006) found that the perception of speech sounds during a listening task activates the same motor circuits involve in the articulatory process for the production of the sounds. Specifically, they found that the lip and tongue motor cortex areas that are implied in articulatory processing, were differentially activated during the perception of lip- and tongue-related phonemes. Murakami et al. (2011) compared motor evoked potential (MEP) amplitudes recorded from the orbicularis oris (OO) muscle while viewing speech-related lip movements, listening to speech, or listening to white noise while viewing visual noise (control conditions). They found that MEP amplitudes from the right OO muscle significantly increased when viewing or listening to speech, in comparison to the control condition. Smalle, Rogers, and Möttönen (2015) found that TMS-induced disruption of the brain regions controlling the movements of the lip muscle, decrease sensitivity in a syllable discrimination task, supporting the argument of motor cortex contribution to perceptual processing of speech sounds.

This role of the motor cortex on the perceptual processing of speech is modulatory, and therefore, not *necessarily* involved in processing speech signals (Hickok & Poeppel, 2004; Hickok, Houde, & Rong, 2011; Hickok & Poeppel, 2007; Möttönen & Watkins, 2009; Skipper, Nusbaum, & Small, 2005; Stasenko et al., 2015). It is hypothesized that the speech input activates auditory-phonological networks, which in turn activate lexical-conceptual networks involved in speech comprehension. This model does not include the motor cortex and therefore, under typical listening circumstances the motor system is not necessarily involved in processing speech signals (Hickok, 2009). Arsenault and Buchsbaum (2015) found no evidence of activation in the motor cortex areas involved in the production of labial and alveolar consonants during a passive auditory perception task. This fMRI study failed to replicate Pulvermüller et al. (2006) results, and suggests that the passive perception of speech sounds does not recruit the motor circuits involve in speech production.

Feed-forward models highlight the relationship between speech acoustic analysis and articulatory processes, but the flow of information is mainly from perception to production (Stasenko et al., 2015). For example, the dual-stream model (Hickok & Poeppel, 2004, 2007; Hickok, 2009), proposes a bilateral *ventral stream* that maps sensory representations onto lexical conceptual representations through multiple routes processing in parallel. This stream involves superior and middle areas of the temporal lobe that supports speech perception and recognition. On the other hand, the *dorsal stream* is left dominant and involves the posterior frontal lobe and posterior dorsal temporal lobe. It supports an interface with the motor system necessary for the acquisition and maintenance of basic articulatory skills and the acquisition of new vocabulary, through sensory representations that guide motor articulatory sequences. Lesions to the ventral stream are expected to impact speech recognition, whereas dorsal-stream lesions are expected to selectively impact speech production, preserving comprehension. For instance, Rogalsky, Love, Driscoll, Anderson, and Hickok (2011) found that aphasia patients with brain lesions affecting motor brain areas showed high levels of performance on receptive speech tasks like word comprehension tests and syllable discrimination tasks, suggesting that the motor speech system is not necessary for speech perception. Auditory-motor interactions are important for language acquisition where a sensory representation of a new word is generated, which is then used through a feed-forward mechanism to guide motor articulatory sequences, while a sensory feedback mechanism monitors and generate corrective speech signals for speech acts (Hickok & Poeppel, 2007). According to this hypothesis, a speech network stemmed from the experience as talkers and listeners, facilitates an interaction between motor and perceptual brain regions, that is, the sensory feedback activates the motor system through correction pathways (feedback control), and activates the auditory speech system from motor regions for tuning motor speech patterns (feed-forward control). As important as is one's speech feedback to generate corrective signals of the articulatory commands to produce speech, others' speech is also used to learn and tune new motor speech patterns. Therefore, activation of motor brain regions during passive speech listening does not indicate a critical role of the motor cortex during perception, but rather, that auditory information is relevant to learn and improve speech production (Hickok et al., 2011).

The Role of M1 on Speech Perception Under Difficult Listening Circumstances

It is uncontroversial that there is a role of motor brain regions during effortful listening, although the exact mechanisms are still unclear. Under optimal listening conditions, speech perception may emerge from acoustic representations within the auditory system, with little or no support from the speech motor system; but under sub-optimal conditions like when the signal is impoverished, masked, or ambiguous, the motor system is recruited and its role in speech perception is especially important (Adank, 2012; Devlin & Aydelott, 2009; Du et al., 2014; Nuttall et al., 2016; Sato et al., 2011; Stasenko et al., 2015; Van Engen & Peelle, 2014). For instance, Du et al. (2014) found a positive correlation between the difficulty in identifying phonemes embedded in noise and BOLD (blood-oxygen-level dependent) activity in speech motor areas, suggesting a compensatory recruitment of the motor cortex in difficult speech perception circumstances. Similarly, Murakami et al. (2011) found a direct correlation between speech listening difficulty and Motor Evoked Potential (MEP) amplitudes, produced when stimulating the OO muscle associated M1. Results showed a significant increase in MEP amplitudes during listening to speech with and without background white noise, when compared to listening of white noise only. Additionally, MEPs were significantly larger when listening to speech embedded in white noise, compared to speech without noise. It is argued that the activation of neurons within the speech motor programs facilitates their connection with sensory maps, supporting a top-down processing of the incoming stimuli that allows the activation of a production-base model of the input to support processing under sub-optimal listening conditions (Badino, D’Ausilio, Fadiga, & Metta, 2014; D’Ausilio, et al., 2012; Tourville & Guenther, 2011; Wilson, 2009).

There is a positive correlation between increasing motor activity from natural to distorted speech perception, with better recognition accuracy of distorted speech (Nuttall et al., 2016). This correlation suggests that the activation of the motor system increases with the difficulty of the perceptual task. In a study where participants were presented with a computer-generated continuum of words between “*head”* and “*had”,* while a robotic device stretched their facial skin and muscles interfering with speech-related mouth movements, an accurate recognition of words was observed for those near the end of the continuum, but a significant perceptual interference was found for the most difficult words with intermediate values between the target words (Ito, Tiede, & Ostry, 2009). Similarly, Nuttall, Kennedy-Higgins, Devlin, and Adank (2017) found that the motor system assist speech perception when listening is difficult, but not when speech intelligibility is only slightly or moderately compromised. Patients with non-fluent Broca's aphasia performed equivalently to patients with right hemisphere damage or healthy older controls in a single-word recognition task, but their performance was significantly diminished in comparison to the other groups of patients, when the task was conducted under altered conditions using a degraded signal (Moineau, Dronkers, & Bates, 2005). Using a behavioral technique based on use-induced motor plasticity, Sato et al. (2011) found that motor training has no effect on the auditory ability to differentiate syllables, but the effect is significant on higher level, top-down categorization processes like when discriminating between minimal phonological pairs embedded in noise. Presumably, the activation of the speech-related motor system during speech listening could play a role in word recognition, especially when a stronger perceptual effort is required (Bidelman & Dexter, 2015; Roy et al., 2008). It is possible that phoneme recognition involves mapping the acoustic signal to motor articulatory networks via the left-hemispheric dorsal speech-processing stream, when other cues like semantics or appropriate context are not available (Adank, Nuttall, & Kennedy-Higgins, 2016; Stasenko et al., 2015). This functionality is relevant considering that in daily life suboptimal auditory input like background noise or a degraded signal (e.g., telephone communication) is the norm and not the exception.

Speech distortions can be grouped based on their origin: (a) External distortions are related to environmental factors like noise, while (b) internal distortions are related to the characteristics of the speaker like accent, style, or vocal tract differences (Bartoli et al., 2013). Nuttall et al. (2017) found that the motor system assists speech perception in both, when speech is embedded in noise (external distortion), and listening to motor-distorted speech (internal distortion). Therefore, motor activation is expected during accented speech perception. Behavioral studies have demonstrated that processing of foreign-accented speech is slower than processing of native-accented speech (Floccia, Butler, Goslin, & Ellis, 2009), response times to accented instructions are longer, error rates are augmented, comprehension levels decrease

(Anderson-Hsieh & Koehler, 1988; Major, Fitzmaurice, Bunta, & Balasubramanian, 2002), and word recognition is more difficult (Leikin, Ibrahim, Eviatar, & Sapir, 2009). A neuroimaging study found that the motor system involved in speech production and speech control, was active during accented speech processing, and it was hypothesized that the speech motor system was active in order to resolve semantic ambiguities and facilitate phonetic identification, which in turn improves L2 speech comprehension (Callan, Callan, & Jones, 2014). It is argued that speech production can aid perception of foreign accented speech, as the listener activates motor representations associated to the motor commands used to produce the word with the native accent. Particularly, when foreign accent promotes recognition doubts in the listener, the production processes could be used to create representations of candidate words to be compared to the speech stimuli and disambiguate the recognition process (Moulin-Frier & Arbib, 2013).

Directions into velocities of articulators. The DIVA model (Directions Into Velocities of Articulators) proposes tuned connections between motor cortex and auditory sensory cortex during speech production, which portrays the role of M1 under difficult speech listening circumstances. The DIVA model is an artificial neural network that describes the sensorimotor interactions involved in articulator control during speech production (Tourville & Guenther, 2011). According to the model, adequate speech production is a consequence of the interaction between motor commands with their sensory consequences. This process is the result of simultaneous neural encoding of coincidences between auditory and somatosensory information, and the causative motor command (Guenther, 2006; Guenther, Ghosh, & Tourville, 2006).

When a speech sound is produced, the feedback control subsystem (FBS) provides online monitoring of the sensory consequences of the acoustic signal. Through the FBS, auditory regions are activated to compare the planned speech sound to the actual information received through feedback. If there are differences, a corrective motor command is sent to the motor cortex. Through this process, auditory and motor information are tuned through corrective commands that are stored in a feed-forward control subsystem (FFS). The FFS controls speech production and becomes more efficient with practice; each speech production attempt will result in a better feed-forward command, thus requiring less auditory feedback, until the FFS is capable of producing speech sounds without error (Guenther et al., 2006; Simmonds, Wise, & Leech, 2011). The speech sound map monitors the relation between acoustic signals of produced utterances and the motor commands that generated them, supporting the constant tuning between the FBS and FFS (Figure 2). It is hypothesized that the motor cortex contains both sensory and motor representations of speech to support FBS and FFS tuning (Cheung et al., 2016). Therefore, listening to speech activates the motor representation of the sound acquired through previous productions. The perceptual and production representations of a word can be connected bidirectionally to a corresponding semantic representation, leading to a triangle of facilitatory connections between perception, production, and semantic representations that may influence word recognition (Zamuner, Morin-Lessard, Strahm, & Page, 2016). If speech listening is difficult, the motor representation activation is especially important, because it may provide complementary information by (a) reconstructing the articulatory process of the acoustic stimuli and (b) enhancing the activation of corresponding sensory maps. This information would support a top-down processing of the challenging incoming stimuli (Badino et al., 2014).

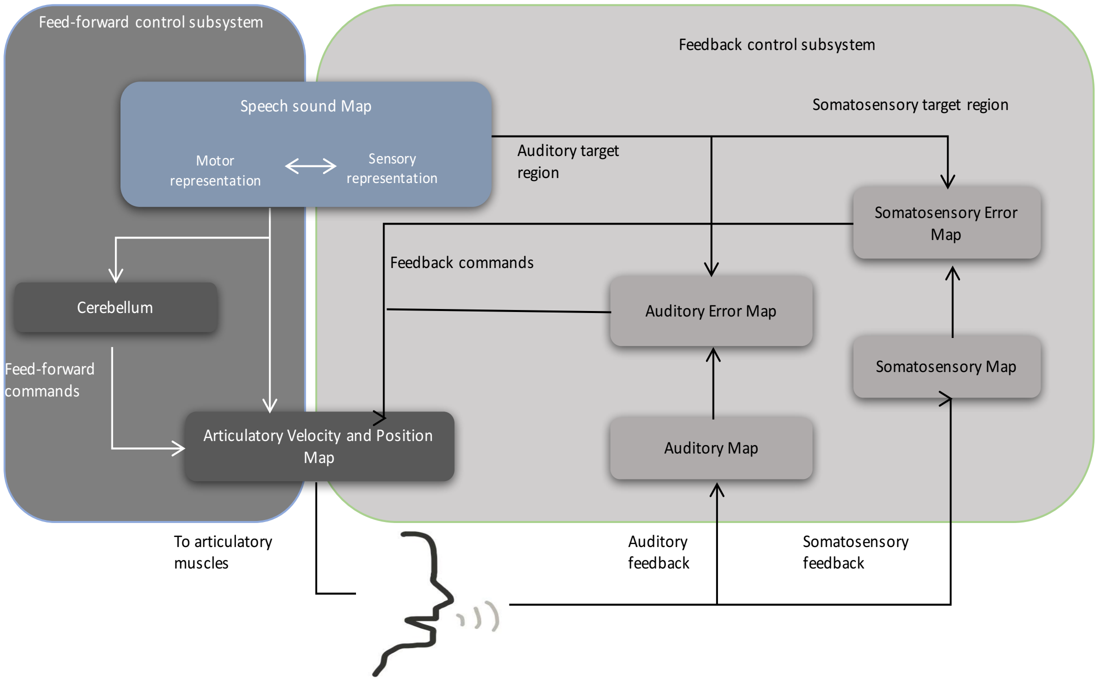

Figure 2. Directions Into Velocities of Articulators (DIVA) model (adapted from Guenther, 2006)

The Role of M1 on Second Language Perception

For a second language learner, language comprehension involves processing under challenging listening conditions due to the lack of experience with the new language sounds (Abutalebi et al., 2009; Chee, Hon, Lee, & Soon, 2001; Costa & Sebastián-Gallés, 2014; Van Engen & Peelle, 2014). The language neural circuitry is developed early in infancy to detect the phonetic and prosodic patterns of speech. This specialized circuitry is designed to maximize the efficiency of language processing by the infant, but once established, it interferes with the capacity to differentiate phonetic sounds and identify rhythmic patterns in a non-native language (Kuhl, 2010; Sebastián-Gallés & Soto-Faraco, 1999), compromising L2 comprehension. The challenging situation of a L2 listener mimics the situation of a listener under sub-optimal conditions; therefore, activation of motor brain regions that supports speech perception is expected. Research with bilinguals in pre-lexical (Callan et al., 2014; Wilson & Iacoboni, 2006) and lexical decision tasks (Burgaleta et al., 2014) suggests that this is the case.

The role of the motor system in non-native sound discrimination is observed very early during infant development. Six-month-old infants from English speaking families, using a flat teething toy that interfered with tongue movements, could not differentiate between Hindi dental /d̪/ and retroflex /ɖ/, while infants using a gummy teether that did not interfere with tongue movements successfully discriminated the non-native contrast (Bruderer, Danielson, Kandhadai, & Werker, 2015). Activation in both auditory and motor brain areas is equivalent during a native and non-native phonetic discrimination task in 7-month-old infants, but by the end of the first year of life, infants' brain activation in auditory areas for native stimuli exceeded that of non-native sounds, and the activation in motor areas was greater for non-native than native speech stimuli (Kuhl, Ramirez, Bosseler, Lin, & Imada, 2014). This finding suggests an important role of motor brain areas during L2 perception from a very early age.

Greater cognitive effort is needed to process words in a less familiar language (Abutalebi et al., 2009; Hernandez, 2009; Hernandez & Meschyan, 2006; Krizman, Bradlow, Lam, & Kraus, 2017; Rodriguez-Fornells et al., 2005; Xue et al., 2004), and the role of the motor system is evident when there is added difficulty in the speech perception task or a higher processing load

(Stasenko et al., 2015). Typically, the motor system generates an internal representation of language sounds that matches the acoustic input (Wilson & Iacoboni, 2006), but less familiar sounds may have less well-tuned representations, requiring more neural activity (Chee et al., 2001). For instance, motor evoked potentials from the anterior tongue muscle are much larger when listening to rare words than while listening to frequent words (Roy et al., 2008). In a foreign language, especially while in the process of learning it, perception of speech sounds and the internal representation do not easily match. Difficult matching emerges from a perceptual bias as a function of the native language phonemic repertoire; becoming aware of the perceptual differences between the sound produced and the accurate speech sound to tune up the internal representation, could be a difficult task when learning a L2, especially after the ability to differentiate the universal set of phonetic contrasts has declined (Kuhl, 2010; Simmonds et al., 2011; Werker & Tees, 1984). This suggests that listening to L2 speech, where there is an incomplete or non-existent representation of the sounds, requires more motor-sensory activation than listening to native speech sounds. When comparing the corticobulbar excitability of the lip muscle while listening to native and non-native speech sounds, Schmitz et al. (2018) found that listening to unknown and untrained phonemes increases the lip muscle excitability. This result suggests that the lack of acoustic-motor models for non-native sounds might lead to motor compensatory activation.

During language acquisition, it is plausible that all words in L2 evoke a comparable involvement of the motor system, because the learner is not able to differentiate them based on their lexical properties. In this situation, it is hypothesized that the FFS supports the perceptual acuity through a top-down mechanism that helps disambiguate phonological information (Du et al., 2014; Tourville & Guenther, 2011). The experience of producing speech allows the listener to generate an internal motor model that serves as hypothesis to be tested against difficult incoming sensory stimuli (Kuhl et al., 2014). Adult learners of non-words were faster to recognized newly learned targets after a production training, in comparison to a heard-only training (Zamuner et al., 2016). Training with visual articulatory feedback containing information about tongue position and mouth openness for non-native vowel production, has demonstrated to be effective to improve production and perception accuracy, suggesting that learning articulatory patterns leads to a "tuning" of the corresponding perceptual representation (Kartushina, Hervais-Adelman, Frauenfelder, & Golestani, 2015). As the learning process advances, frequent words become integrated into the lexicon and their recognition becomes easier, and in consequence the role of the motor system becomes less critical. Its contribution will be required when listening to known, but rare words, as well as in ambiguous situations, like in noisy environments (Roy et al., 2008).

During language production, the L2 speaker faces the challenge of developing articulatory motor commands for reproducing non-native perceptual patterns. Some research supports the idea that frequent input of native language sounds activates the same specific motor circuits involved in articulatory processing when producing speech sounds; this neural activity correlation between auditory and articulatory systems generate an articulatory-acoustic feed-forward loop (Pulvermüller et al., 2006). With multiple repetitions the loop is strengthened supporting auditory-articulatory links that facilitate speech production (Schomers et al., 2015; Stokes & Surendran, 2005). The late L2 learner does not have the appropriate articulatory-acoustic patterns to produce non-native phonemes, because substitutions are made when there are similarities between languages. For example, a Spanish speaker perceives similarly the native /d/ and non-native "*th*" voiced sound (/ð/) at the beginning of a word, hence the production is not adapted and words like "*they*" and "*day*" end up sounding the same. This perceptual bias as a function of the L1 phonemic repertoire has an influence on L2 production (Simmonds et al., 2011), which helps initially to improve fluency and communication, but in the long term may perpetuate the use of L1 articulatory patterns in L2, and enhance the difficulty in correcting erroneous articulatory transfer (MacWhinney, 2005). Consequently, for the L2 speaker the articulatory patterns of native sounds are easier to produce than those of non-native sounds. This articulatory demand adds cognitive effort to the already challenging situation of the L2 speaker.

The contribution of the motor system to speech perception may be more evident when discriminating sounds associated with complex motor control, as opposed to motorically simple discriminations (Bartoli et al., 2013; Hernandez & Meschyan, 2006; Liu, Hu, Guo, & Peng, 2010; Pulvermüller & Fadiga, 2010). It is unclear, however, whether listening to non-native phonemes with reduced frequency of articulatory rehearsal in L2 requires additional motoric activation (Costa & Sebastián-Gallés, 2014), or if motor activation in L2 perception is not correlated with the production difficulty of non-native phonemes (Wilson & Iacoboni, 2006). Apparently, the perceptual analyses of ill-formed syllables (those with low frequency, complex structural formedness, and very difficult to articulate across languages) do not produce additional activation in the motor lip region, suggesting that the motor system support is active only when listening to well-formed linguistic structures similar to the ones that exist in the listener's language (Berent et al., 2015).

Transcranial Magnetic Stimulation (TMS) in Speech Research

Transcranial magnetic stimulation (TMS) is a powerful tool for investigating the role of the articulatory motor system in speech processing (Adank et al., 2016; Devlin & Watkins, 2007; Iacoboni, 2008; Möttönen & Watkins, 2009, 2012; Murakami, Kell, Restle, Ugawa, & Ziemann, 2015; Nuttall et al., 2016). Unlike fMRI and EEG, TMS allows testing causal links between neural activity and behavioral task performance (Murakami et al., 2013; Skipper, Devlin, & Lametti, 2017). TMS is an optimal tool for research on functional interactions and changes in motor cortex during language processing, because of its non-invasiveness, reversibility, and temporal precision (Vukovic et al., 2016). Speech research using TMS has provided evidence of motor activation during syllable recognition (Bartoli et al., 2013; Berent et al., 2015; D'Ausilio et al., 2009; Meister et al., 2007; Möttönen, Dutton, & Watkins, 2013; Mottonen, van de Ven, & Watkins, 2014; Rogers, Mottonen, Boyles, & Watkins, 2014; Sato, Buccino, Gentilucci, & Cattaneo, 2010; Smalle et al., 2015), M1 influence on speech perception (Fadiga et al., 2002; Murakami et al., 2015; Murakami et al., 2011; Nuttall et al., 2016; Repetto, Colombo, Cipresso, & Riva, 2013; Roy et al., 2008; Schomers et al., 2015; Tremblay, Sato, & Small, 2012; Watkins, Strafella, & Paus, 2003), positive correlation between speech perception task difficulty and M1 activation (D'Ausilio, et al., 2012; Murakami et al., 2011; Nuttall et al., 2017), and motor support during listening to non-native phonemes (Schmitz et al., 2018).

A TMS device consists of a few circular turns of copper wire connected to the terminals of an electrical capacitance. The capacitance discharges a large current flow through the wire coil

(Figure 3), generating a magnetic field. Stimulation of the human brain involves the depolarization of neuronal membranes in order to initiate action potentials, thus, the coil is placed on the scalp of the participant, who is stimulated by the short but relatively strong magnetic field. TMS uses electromagnetic induction to generate effectively and painlessly a suprathreshold electrical current in the neural tissue under the scalp (Adank et al., 2016; Rossini et al., 2015). The electrical pulse has an overall duration of less than 1 msec (Walsh & Pascual-Leone, 2003). Single pulses of TMS applied to M1 can generate a motor evoked potential (MEP; Jannati, Block, Oberman, Rotenberg, & Pascual-Leone, 2017), an action potential in the target muscle that can be recorded using electromyography (EMG). The intensity of the pulse required to elicit an MEP, and the resulting MEP amplitude differs across participants, reflecting neuroanatomical differences, skull thickness, and the functional state of the motor system (Möttönen et al., 2014).

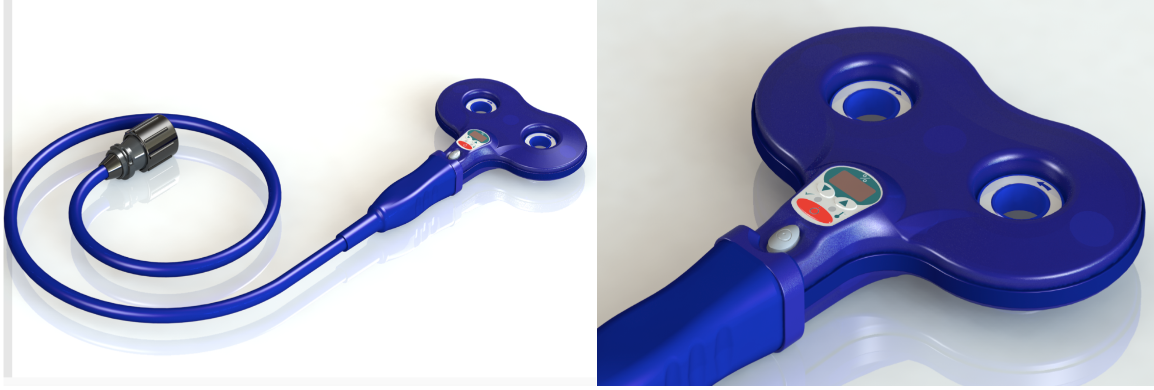

Figure 3. Transcranial Magnetic Stimulation coil (© Copyright 2018 Magstim, https://www.magstim.com/products/coils)

Repetitive TMS (rTMS) is a stimulation method where successive TMS pulses are delivered. rTMS always result in excitation of the cortex, but the overall effect on a behavioral task may be inhibitory or excitatory depending on the duration, frequency, and timing of stimulation, and the stimulated area of the cortex (Adank et al., 2016). The excitatory or inhibitory aftereffects can last several minutes after the stimulation. Excitatory effects appear to reflect rTMS-induced changes in the strength of glutamatergic synapses via NMDA receptors, AMPA receptors and calcium channels. On the other hand, inhibitory effects may reflect changes in GABAergic neurons. Given the modulatory impact of rTMS protocols on brain physiology, their effects critically depend on brain state during stimulation (Polanía, Nitsche, & Ruff, 2018). Typically, low frequency (≤1 Hz) rTMS reduces cortical excitability, whereas high-frequency (5–20 Hz) rTMS has the opposite effect (Cirillo et al., 2017). Romero, Anschel, Sparing, Gangitano, and Pascual-Leone (2002) found that a 10 minute rTMS train at 1-Hz and subthreshold intensity decreases corticospinal excitability for up to 15 min after the train. The typical rTMS temporary disruption or "virtual lesion" (Pascual-Leone et al., 2000; Walsh & Pascual-Leone, 2003) to speech processing areas, may modulate the performance on speech recognition tasks. Nevertheless, rTMS cannot fully disrupt functioning of the stimulated areas, therefore participants are able to move with imperceptible behavioral consequences and minimal discomfort (Möttönen & Watkins, 2012).

An area of concern about rTMS protocols is the enormous variability of its output. Although inhibition is the typical effect found after a low frequency rTMS protocol (Cirillo et al., 2017; Möttönen et al., 2014; Romero et al., 2002; Rossi, Hallett, Rossini, & Pascual-Leone, 2009; Rossini et al., 2015), previous research has reported high variability on MEP amplitude aftereffect, and in some instances, even an opposite (facilitatory) effect is observed (Fitzgerald, Fountain, & Daskalakis, 2006; Houdayer et al., 2008; Jannati et al., 2017; Maeda, Keenan, Tormos, Topka, & Pascual-Leone, 2000; Nettekoven et al., 2015; Ridding & Ziemann, 2010). Strigaro, Hamada, Cantello, and Rothwell (2016) tested the effect of a 15-minute train of 1-Hz rTMS on the first dorsal interosseous (FDI) associated motor cortex, to 32 healthy participants. They compared the MEP size recorded from the FDI muscle before and after the stimulation. The study found that 50% of the participants had minor or no response to the rTMS, while the remainder 50% showed a facilitatory effect (larger MEP amplitude). Participants that show the expected effect after rTMS are known as "*responders*", and those who do not show the expected response or show the opposite response are "*non-responders*" (Lopez-Alonso, Cheeran, Rio-Rodriguez, & Fernandez-Del-Olmo, 2014).

Several studies using non-invasive inhibitory brain stimulation protocols have reported between 50% and 58% of non-responders among their healthy research participants (Jannati et al., 2017; Lopez-Alonso et al., 2014; Nettekoven et al., 2015; Strigaro et al., 2016). It is hypothesized that rTMS stimulates axons rather than cell bodies of neurons, because the latter have a higher threshold. Thus, the effectiveness of rTMS depends on the type of axons that the electrical pulse stimulates. Facilitatory interneurons are preferentially arrayed in one particular direction, while inhibitory interneurons are oriented in random directions within the motor cortex (Arai et al., 2005). The direction of interneuron axons and the number of fired neurons are determined by individual differences (Nojima & Iramina, 2018). Meta-analysis studies have found several factors that may explain the inter-individual variability of non-invasive brain stimulation techniques. These factors include gender, cranial and brain anatomy, aerobic exercise, baseline level of cognitive and motor function, time of the day, age, attention, synaptic history (history of synaptic activity within a stimulated cortical region), pharmacological influence, and genetics (Li, Uehara, & Hanakawa, 2015; Ridding & Ziemann, 2010). Furthermore, Rogers and Dhaher (2017) found that the rTMS effect is mediated by the expression of sex hormones, and therefore, the cyclic fluctuation of female hormones is a contributor to rTMS response variability. All these sources of physiological variability suggest that it should not be assumed that protocols of non-invasive brain stimulation known to result in facilitation or inhibition of M1, will have a predictable effect on all the participants of a study (Polanía et al., 2018; M. T. Wilson & St George, 2016). Therefore, reliable aftereffect measures are important to adequately classify research participants based on their individual response to rTMS protocols.

Alternative to Motor Evoked Potential (MEP) as rTMS physiological outcome measure. Inhibitory and excitatory aftereffects of rTMS are determined by measuring MEP amplitude following the stimulation to M1 areas linked to targeted muscles; a decrease in amplitude of MEPs is considered an inhibitory or suppressive effect, and an increase is an excitatory or facilitatory effect of TMS on M1 (Adank et al., 2016). Although the typical output measure of rTMS is the MEP amplitude change, it is an indirect measure that is difficult to relate to changes in the cortex, and may not always be a reliable indicator of the efficacy of non-invasive brain stimulation protocols (Rogers, Mottonen, Boyles, & Watkins, 2014; Wilson & St George, 2016).

The development of new output measures to determine the aftereffects of rTMS are necessary to validate the effectiveness of rTMS protocols, and yield more precise data that links behavioral to cortical changes. The vowel space area (VSA) may be an alternative measure to MEPs. It is a measure of vowel dispersion in the space, typically used to characterize speech motor control (Berisha, Sandoval, Utianski, Liss, & Spanias, 2014). This measure is defined as the two-dimensional area bounded by lines connecting the first and second formant frequency coordinates (F_1 and F_2) of vowel productions, which has shown to correlate with intelligibility in dysarthric speech (Berisha et al., 2017; Skodda, Grönheit, & Schlegel, 2012; Skodda, Visser, & Schlegel, 2011). The development of automatic assessments of VSA (Berisha et al., 2017; Sandoval, Berisha, Utianski, Liss, & Spanias, 2013; Tu, Wisler, Berisha, & Liss, 2016) makes this measure a viable alternative to MEPs as indicator of the efficacy and aftereffects of rTMS.

Specific Aims

There is evidence that recruitment of the M1 is common in speech perception tasks that involve degraded speech or effortful listening conditions (Badino et al., 2014; D'Ausilio, et al., 2012; Du et al., 2014; Repetto et al., 2013; Schomers et al., 2015; Schomers & Pulvermüller, 2016). Although the challenge of recognizing and discriminating non-native speech appears to be an instantiation of listening under difficult circumstances, it is still unknown if M1 recruitment is facilitatory to L2 speech perception. The purpose of this study was to investigate the role of cortical speech motor centers, as indexed by a lip muscle activation, in processing acoustic inputs in the native and non-native languages, using rTMS to selectively alter neural activity in M1. This is the first study to use rTMS as a tool to identify the role of M1 during L2 speech recognition. Due to the large inter-individual variability of the amplitude of rTMS-induced motor evoked potentials (MEPs) an additional dependent measure, vowel space area (VSA) was tested as an alternative measure of the speech production aftereffects of low frequency rTMS. More specifically, the present study aims to test the following hypotheses:

Specific Aim 1. To identify the role of the lip associated M1 during word recognition.

Hypothesis 1. Selective alteration of M1 yields more interference in a word recognition task, in comparison to a sham condition where M1 is not altered. Participants performed on a listening word-to-picture matching task after rTMS and sham-rTMS. Low frequency rTMS on M1 was expected to lengthen reaction times and increase the number of errors in word recognition compared to the sham condition.

Hypothesis 2. Selective alteration of M1 yields more interference in the recognition of L2 words than of L1 words. Participants performed on L1 and L2 listening word-to-picture matching task. M1 rTMS was expected to lengthen reaction times and increase the number of errors in L2 word recognition compared to L1.

Specific Aim 2. To determine the efficacy of VSA as a measure of the aftereffect of low frequency rTMS on the lip-associated M1.

Hypothesis 3. If VSA is an efficacious measure of the aftereffect of low frequency rTMS, significant differences in VSA between pre- and 5- and 15-minutes post-rTMS were expected.

Voice recordings on L2 pre- and post-rTMS were analyzed using an automated assessment to measure changes on VSA.

Method

Participants

Thirty-six (23 females, mean ± SD age, 26.2 ± 8.3 years), bilingual speakers of Spanish and English (15 Spanish-native speakers), healthy, right handed adults (Edinburgh Handedness Inventory; Oldfield, 1971), participated in this study for financial compensation. Participants answered the Language Experience and Proficiency Questionnaire (LEAP-Q; Marian, Blumenfeld, & Kaushanskaya, 2007), for a L2 proficiency and accent score, and performed on the Receptive One-Word Picture Vocabulary Test Spanish Bilingual Edition (ROWPVT-4: SBE; Martin, 2012) on their second language, for a vocabulary knowledge score. The participants' profiles are summarized in Table 1.

All participants reported normal or corrected-to-normal vision, normal hearing, and no professional musical training. No history of neurological disease, psychiatric syndrome, trauma, or any other TMS contraindications were reported using a TMS safety screening questionnaire (adapted from: Keel, Smith, & Wassermann, 2000; Rossini et al., 2015; Appendix A). Prior to their participation in the study, all volunteers gave written informed consent. The procedure was approved by the Institutional Review Board committee at Arizona State University (Appendix B) in accordance with the Declaration of Helsinki.

Table 1

Participant's Demographics

	N	Age (min,max)	L2 AOA (min, max)	L2 Proficiency (SD)	L2 Accent (SD)	ROWPVT (SD)
Females	23	25.4 (19, 52)	6.9 (0, 19)	7.35 (1.3)	6.4 (2.8)	97.8 (11.4)
Males	13	27.5 (18, 53)	9.1 (0, 24)	7.23 (2.6)	5.1 (2.7)	101.9 (15.7)
L1-English	21	21.9 (18, 33)	7.1 (0, 19)	6.83 (1.9)	5.5 (2.7)	97.2 (9.1)
L1-Spanish	15	32.3 (19, 53)	8.4 (1, 24)	7.97 (1.7)	6.6 (3.0)	102.1 (17.1)
Total	36	26 (18, 53)	7.7 (0, 24)	7.3 (1.9)	5.9 (2.8)	99.3 (13.04)

Notes. L1 = Native language; L2 = Second language; AOA = Age of acquisition; ROWPVT = Receptive One-Word Picture Vocabulary Test Spanish Bilingual Edition; SD = Standard deviation

Stimuli

Sixty-four high frequency English words were selected from the SUBTLEX$_{US}$ corpus (Brysbaert, & New, 2009), and 64 Spanish high frequency words were selected from the

Clearpond-Spanish corpus (Marian, Bartolotti, Chabal, Shook, 2012). The 64 words in each language corresponded to 32 minimal pairs, that is, pairs of words that differ only in one phonological element (see Appendix C for a complete list of experimental words). To prevent the participants from recognizing the phonological nature of the experiment, 50 filler words in each language were also included in the task. All 228 words (128 experimental, 100 filler) were randomly assigned to list A or list B. Each list included 32 experimental words in English, 32 experimental words in Spanish, 25 filler words in English, and 25 filler words in Spanish, for a total of 114 words in each list.

Lists A and B were recorded word by word, using a female voice from a text-to-speech Web-application (TTSReader, Wellsource Ltd. 2017). The voices used for each language were as similar as possible to each other, to prevent language identification based on the stimulus voice. Because previous research reported a positive correlation between speech perception difficulty and M1 activation (D'Ausilio, et al., 2012; Murakami et al., 2011; Nuttall et al., 2017), all words were embedded in white noise using MATLAB (MathWorks), at a signal-to-noise ratio (SNR) of -2 db. This SNR has been previously used in research of speech processing in noise (Adank, Davis, & Hagoort, 2012; Du et al., 2014; Du, Buchsbaum, Grady, & Alain, 2016). For each stimulus word, experimental and filler, a corresponding matching picture was chosen. The picture showed an object or a situation the word typically represents.

Behavioral Task

A word-to-picture matching task was set up using PsychoPy© (Peirce, 2009). A word embedded in noise was presented, and 4 pictures appeared on the screen. The pictures presented for each stimulus included the matching picture (correct answer), a phonological distractor (minimal pair), a semantic distractor (similar meaning), and an unrelated distractor. Each stimulus could not be heard more than once.

During the experimental sessions, participants performed on the word-to-picture matching task before and after rTMS intervention, hereafter named pre-rTMS and post-rTMS, respectively. Lists of words A and B were presented counterbalanced across participants during the pre, or post trials. The 114 stimuli in each list were randomly presented. The participants were instructed to (a) listen to the word stimulus presented through headphones, and (b) to choose the picture presented on the screen that semantically corresponds to the word stimulus, using the computer keyboard (Figure 4). Reaction times (RT) and accuracy were recorded.

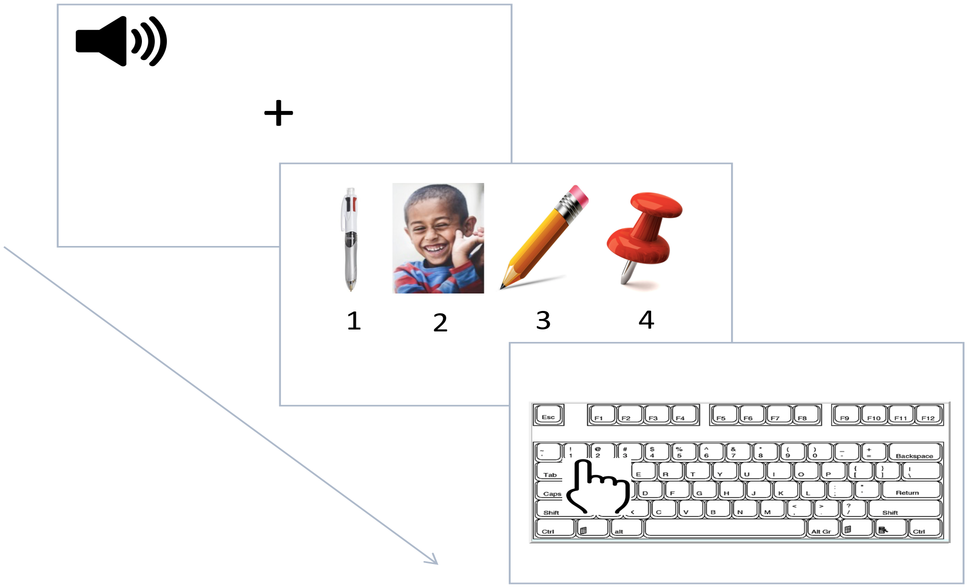

Figure 4. Word-to-picture matching task. Participant listen to a word stimulus embedded in noise, and chose the corresponding image between 4 alternatives presented, using the number keys (1, 2, 3, or 4) on the computer keyboard.

Repetitive Transcranial Magnetic Stimulation (rTMS)

This study followed the general rTMS protocol described by Möttönen et al. (2014), to examine the role of the primary motor cortex (M1) representation of the lip area in speech perception. The participant sat upright and relaxed in front of a computer screen, on a comfortable chair with the head supported by a headrest. Surface electromyography (EMG) activity was recorded from the upper-right quadrant of the orbicularis oris (OO) muscle, using an active bipolar surface electrode following standard skin preparation. The raw EEG signals were amplified (x1000; Delsys Bangnoli amplifier system), band-pass filtered (10-1000Hz), sampled at 5-kHz (Micro 1401; Cambridge Electronic Design, Cambridge, UK), and digitally stored in a personal computer for offline analysis. Single-pulse TMS and rTMS were delivered with a 70-mm outer diameter figure-of-eight coil that connected Magstim rapid^2 stimulator with a monophasic current waveform (Magstim Company, Dyfed, UK).

The first step was to localize the OO muscle representation within the left M1. To identify this area, the first dorsal interosseous (FDI) “motor hotspot” was used as a guide to subsequently localize the OO muscle area. To find the FDI “hot spot” the TMS coil was placed 33% of the way between the Cz reference point and the left preauricular point, oriented 45-degrees obliquely to the sagittal midline. The first TMS pulse was delivered at a medium intensity (50% of the maximum stimulator intensity); if no motor evoked potential (MEP) was elicited, the coil was moved by 0.5-cm steps around the area, and intensity was gradually increased until finding the appropriate FDI “hotspot”. To find the lip associated motor area, participants were asked to contract the lips by rounding and protruding them corresponding approximately to 5-10% of the maximum voluntary contraction (MVC). The participants received visual feedback from the computer screen on their EMG activity, and were instructed to keep a constant lip contraction throughout the procedure as well as data collection. The coil was placed 2-3 cm from the FDI hotspot along a straight line towards the corner of the left eye (Möttönen et al., 2014), and a pulse was delivered at a medium intensity. If no MEP was elicited, the coil was moved by 0.5-cm steps around this area. The motor hotspot of the OO muscle was defined as the site where TMS consistently elicited the maximal MEP in the OO muscle. The coil was held tangentially to the scalp with the handle pointing backwards at 45-degree angle from the sagittal plane, inducing a posterior to anterior current (Kaneko, Kawai, Fuchigami, Morita, & Ofuji, 1996; Nakamura, Kitagawa, Kawaguchi, & Tsuji, 1997). For ensuring reliable coil placement throughout the data collection, the coil position was marked on a cap worn by the subjects, with a soft-tip pen. Active motor threshold (AMT) for the OO muscle was defined as the minimum intensity that elicited >100 μV MEPs in 5 out of 10 consecutive trials during a weak sustained muscle contraction (5-10% MVC) of the OO muscle. Stimulus intensities were expressed as a percentage of the stimulator output (%MSO). The average AMT for the 36 participants was 50.5% ±5.1%MSO.

For the MEP recordings in the OO muscle, test intensity for single-pulse TMS was set at 120% of AMT throughout the whole data collection. TMS was delivered over the left M1 representation of the OO muscle every 6 seconds ±10% while the subjects maintained lip muscle contraction at around 10% MVC. Twenty MEPs were recorded before and 3 minutes after the 15 min-rTMS intervention as a manipulation check of rTMS. Our rTMS procedure and measurement followed standard guidelines (Chipchase et al., 2012).

For the rTMS administration, a figure-of-eight coil of similar dimension was positioned over the left hemisphere motor hot spot for the OO muscle. Stimulus intensity was set at 100% of AMT in the OO muscle associated M1. Low-frequency rTMS of 0.6 Hz (0.6 Hz-rTMS) was delivered over the marked spot on the left M1 for 15 minutes. Likewise, sham rTMS (i.e., placebo) was given through the same coil with identical parameters, but the coil was flipped perpendicularly to the scalp for preventing the coil from flowing magnetic pulses into the brain (Figure 5). However, the participants could feel the coil contact with the scalp and listen the stimulation click sounds. During the rTMS application, the subjects were asked to completely relax their OO muscle. The entire rTMS protocol exactly followed previous literature demonstrating modulations of the lip area of M1 excitability by means of the rTMS approach (Smalle et al., 2015).

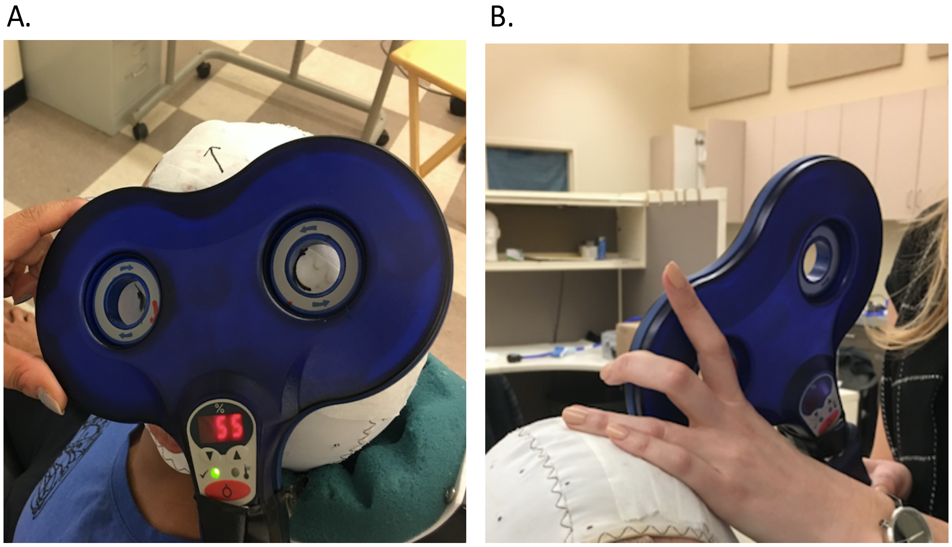

Figure 5. Coil position during real (A) repetitive Transcranial Magnetic Stimulation (rTMS), and sham (B) rTMS.

Procedure

All participants completed two rTMS (i.e., real and sham) sessions at least one week apart in a randomized double-blind crossover design. Before the first experimental session, participants answered, online, the Language Experience and Proficiency Questionnaire (LEAP-Q; Marian, Blumenfeld, & Kaushanskaya, 2007) for English (for Spanish native speakers) or Spanish (for English native speakers; Appendix D), and the handedness inventory (Edinburgh Handedness Inventory; Oldfield, 1971. Appendix E). The first session began with the reading and explanation of the informed consent (Appendix F). After the informed consent was signed, the participant answered the TMS safety screening questionnaire (Appendix A). Participants sat on a comfortable chair with arm and headrests, wore a cap to facilitate the drawing of marks for coil position on the head, and electrodes were placed on OO muscle and forehead (ground electrode). The participants' voice was recorded reading a passage in English and Spanish (Appendix G), and completed the word-to-picture matching task (previously described), using list A or B with order counterbalanced across participants. Following the behavioral task, the TMS procedure began: The OO muscle representation area was localized, the AMT was determined, and pre-rTMS MEP amplitude measures were collected. Participants watched an animated cartoon without sound on the computer screen during the 15 minute rTMS. Three minutes after rTMS, post-rTMS MEP size measures were collected. A second voice recording was collected, reading only the passage on the participant's second language. The alternative list (B or A) was used on the behavioral word-to-picture matching task, and a final voice recording was collected with readings in both languages (see Figure 6 for an outline of the experimental sessions).

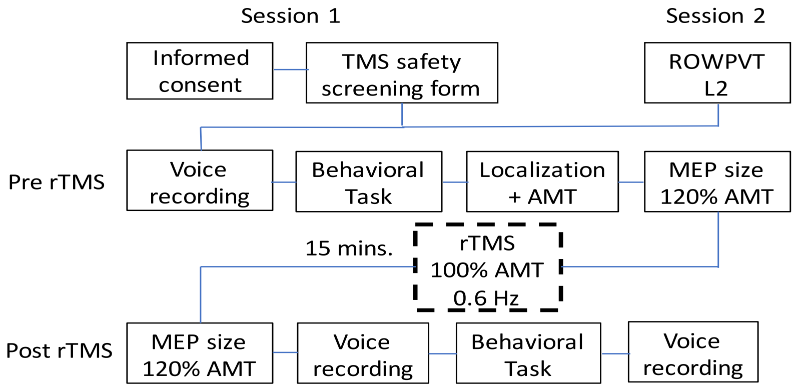

Figure 6. Procedure in session 1 and 2. TMS = Transcranial Magnetic Stimulation. ROWPVT = Receptive One-Word Picture Vocabulary Test Spanish Bilingual Edition. AMT = Active Motor Threshold. MEP = Motor Evoked Potential.

The second session began with the application of the Receptive One-Word Picture Vocabulary Test Spanish Bilingual Edition (ROWPVT) in the participant's second language. The following procedure was exactly the same as the procedure for the first session, after signing the informed consent.

Data Analysis

Motor Evoked Potentials (MEPs). For the MEPs index, MEP area rather than MEP amplitude was used because the obtained measures exhibit polyphasic waveforms. MEP area was calculated for each trial as integral of rectified EMG in the right OO muscle within a 45-ms window ranging from 15 to 60 ms after TMS onset. The background pre-trigger EMG (bEMG) in integral of rectified EMG within a 100-ms window before rTMS onset was also calculated for ruling out the possibility of an effect of bEMG on MEPs change. For each trial, MEPs were discarded, if they exceed on average ±2 SD of the MEP area. In total 4.4% of MEPs were discarded for subsequent analysis. The values of MEP areas obtained pre-rTMS were subtracted from those obtained post-rTMS and are expressed as ΔMEP. After the sequence of procedures, ΔMEP, MEP area in pre-rTMS, and bEMG were fed into statistical analyses. All of the MEP data analyses were performed with a custom-written code implemented in Matlab. Pre- and post-rTMS MEPs were compared using a paired t-test.

The MEP analysis showed reliable measures on 24 out of the 36 participants. A failure in eliciting MEPs, or a MEP latency below 10ms across all trials was observed in the 12 remaining participants. Previous literature demonstrated that evoked potentials in the OO muscle with a latency below 10ms are likely elicited by directly stimulating the facial nerve (Devlin, Watkins, 2008; Murakami et al., 2011). Thus, data from 24 participants was used for subsequent analyses (Figure 7). A two-way repeated-measures analysis of variance (rmANOVA) was performed to assess if the modulation of M1 by 0.6-Hz-rTMS yielded a significant effect on MEP area compared to a control (sham) condition. The analyzed factors were condition (experimental vs. control, or real vs. sham), and rTMS effect (pre- vs. post-rTMS).

Recent empirical evidence shows large inter-individual variability on the induced effects of non-invasive brain stimulation techniques, due to anatomical, physiological, and neurochemical differences among individuals (Hamada, Murase, Hasan, Balaratnam, & Rothwell, 2013; Li et al., 2015; Lopez-Alonso et al., 2014; Ridding & Ziemann, 2010). In other words, every rTMS protocol will produce responder and non-responder participants. In this study, a number of participants did not exhibit the expected decrease in MEPs during post rTMS relative to pre-rTMS (i.e., non-responders). We therefore identified non-responders based on the following criterion: Participant with ΔMEP >0 were classified as non-responders. A total of 11 participants met this criterion. We assigned 13 and 11 participants to 'responder or inhibitory' and 'non-responder or facilitatory' groups, respectively. Conclusively, we analyzed MEP and behavioral data for each group separately.

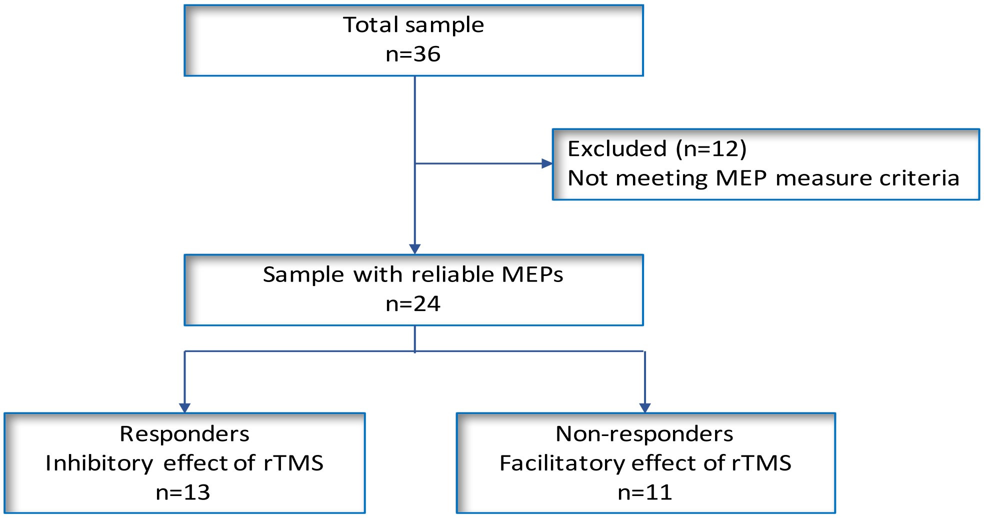

Figure 7. Participants flow for data analysis. MEP = Motor Evoked Potential. rTMS = repetitive Transcranial Magnetic Stimulation.

A two-way rmANOVA was performed on each group (inhibitory and facilitatory) to assess the effect of selective alteration of M1 on MEP area compared to a control (sham) condition. The analyzed factors were condition (experimental vs. control, or real vs. sham), and rTMS effect (pre- vs. post-rTMS). The MEP area statistical analyses were conducted using JASP Team (2018) version 0.8.5 computer software, and effects were tested at a significant level of $p < 0.05$.

Behavioral Task Accuracy and Reaction Time (RT). Accuracy and reaction times (RT) on the word-to-picture matching task were recorded using PsychoPy© (Peirce, 2009). Descriptive statistics of accuracy and RT of 36 participants on the behavioral task pre- and post-rTMS trials are reported. A three-way rmANOVA was performed to assess if the modulation of M1 by 0.6-Hz-rTMS yielded a significant effect on a word identification task compared to a control (sham) condition, and if there was a significant difference between the effects on L2 compared to L1. The analyzed factors were condition (experimental vs. control, or real vs. sham intervention), language (L1 vs. L2), and rTMS effect (pre- vs. post-rTMS trials). Follow-up analyses were conducted using paired *t-tests* with Holm's sequential Bonferroni adjustment.

A three-way rmANOVA was performed on each group (inhibitory and facilitatory) to assess the effect of selective alteration of M1 on a word identification task compared to a control (sham) condition, and if there was a significant difference between the effects on L2 compared to L1. The analyzed factors were condition (experimental vs. control, or real vs. sham intervention), language (L1 vs. L2), and rTMS effect (pre- vs. post-rTMS trials). Follow-up analyses were conducted using paired *t-tests* with Holm's sequential Bonferroni adjustment. The behavioral statistical analyses were conducted using JASP Team (2018) version 0.8.5 computer software, and effects were tested at a significant level of $p < 0.05$.

Vowel Space Area (VSA). Speech changes produced as a result of the low frequency rTMS procedure were assessed in the total sample. Three voice recordings per participant (pre-RTMS, approximately 5- and 15-minutes post-rTMS) on L2, were analyzed to measure the VSA using an automated assessment (Berisha et al., 2017; Sandoval, Berisha, Utianski, Liss, & Spanias, 2013). VSA is a measure of produced vowel dispersion, identified as a correlate of intelligibility in patients with dysarthria (Skodda et al., 2011). A one-way repeated-measures ANOVA was performed to each group (inhibitory and facilitatory), to assess the effect of rTMS on speech intelligibility 5- and 15-minutes after the procedure.

Results

Motor Evoked Potentials (MEPs)

The individual analyses of MEPs showed reliable measures on 24 out of the 36 participants. Only data from the selected 24 participants were used for subsequent MEP-area analyses. MEP data were log-transformed prior to analysis to meet statistical assumptions. Descriptive data of MEP areas is presented on Table 2. A two-way rmANOVA showed no significant main effects of experimental condition ($F_{(1,23)} = 0.058$, $p = 0.81$, $\eta^2 = 0.002$) or rTMS effect ($F_{(1,23)} = 2.66$, $p = 0.12$, $\eta^2 = 0.10$). The interaction effect between experimental condition and rTMS was also non-significant ($F_{(1,23)} = 0.44$, $p = 0.52$, $\eta^2 = 0.02$). Because the inter-individual variability in MEP-OO area may have masked the effect of rTMS, MEP data were separated into responders (inhibitory effect of rTMS), and non-responders (responded with an unexpected facilitatory effect of rTMS) groups (Figure 8).

Table 2.

Motor Evoked Potentials Descriptive Statistics

Condition	rTMS	Mean	SD	N
Experimental	Pre	-1.342	0.797	24
	Post	-1.468	0.691	24
Control	Pre	-1.268	0.59	24
	Post	-1.471	0.51	24

Note: rTMS = repetitive transcranial magnetic stimulation; SD = standard deviation; N = number of participants.

In the responders (inhibitory) group (n = 13), no significant difference was observed between the experimental and control condition in the MEP area change (ΔMEP) between pre- and post-rTMS ($t_{(12)} = -1.13$, $p = 0.28$, $d = -0.31$). Nevertheless, the difference was in the expected direction: on average, the MEP area decreased 48% between pre- and post-rTMS in the experimental condition, compared to a 26% reduction in the control condition (Figure 8). On the other hand, a significant difference in the opposite direction was observed between the experimental and control condition in the ΔMEP of non-responders (facilitatory) group (n = 11; $t_{(10)} = 3.04$, $p = 0.01$, $d = 0.92$). On average, the MEP area of non-responders ***increased*** 34%

between pre- and post-rTMS in the experimental condition, and ***decreased*** 9% in the control condition (Figure 8). Taken together, these effects suggest a tendency for MEP area to decline between assessments. The significant increase in the non-responders group should be interpreted with caution: the effect is opposite to what is expected from a low frequency rTMS procedure, and therefore the reliability of the classification of these participants as non-responders is uncertain, and a regression to the mean effect cannot be ruled out.

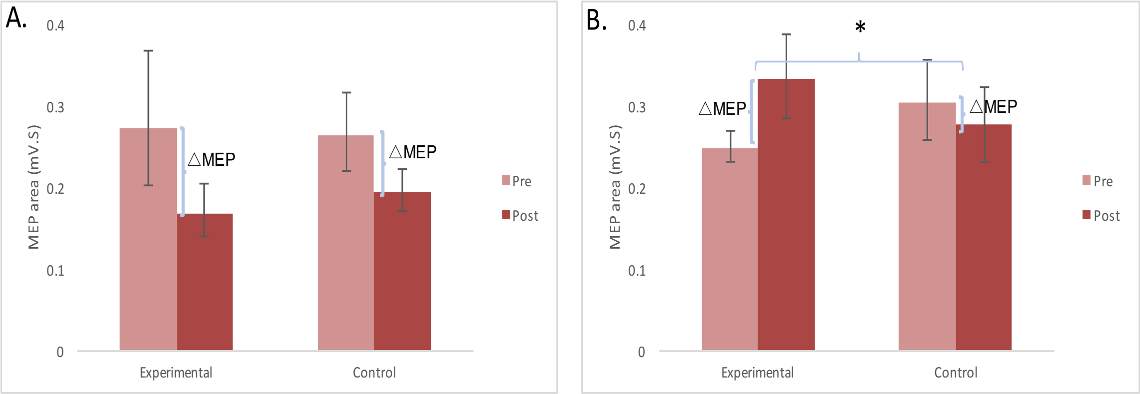

Figure 8. Mean (±SEM) MEP area change between pre- and post-rTMS in the experimental and control conditions. Panel A shows MEP changes for responders (inhibitory) group; panel B shows MEP changes for the non-responders (facilitatory) group.

Behavioral Task Accuracy

Accuracy scores for the total sample (n = 36) are presented on Table 3. All participants performed substantially better than chance level (chance level = 8 correct responses out of 32 possible correct). The three-way rmANOVA revealed a significant main effect of language ($F_{(1,35)} = 86.52$, $p<.001$, $\eta^2 = 0.71$), and rTMS ($F_{(1,35)} = 18.48$, $p<.001$, $\eta^2 = 0.35$), but not of experimental condition ($F_{(1,35)} = 1.045$, $p = 0.31$, $\eta^2 = 0.03$). The effect of language was explained by a higher accuracy in L1 compared to L2 in all conditions. The effect of rTMS shows that post-rTMS performance was more accurate than pre-rTMS (Figure 9); the *post hoc t-tests* with Holm's sequential Bonferroni adjustment showed a significant improvement in accuracy in the control condition for the L2 ($t_{(35)} = -2.73$, $p = 0.010$). Differences were non-significant for L1 in the control and experimental conditions ($t_{(35)} = -1.78$, $p = 0.08$, and $t_{(35)} = -1.12$, $p = 0.27$ respectively) and for L2 in the experimental condition ($t_{(35)} = -0.52$, $p = 0.61$). Expected two-way interaction (Condition*

Language: $F_{(1,35)} = 0.04$, $p = 0.85$, $\eta^2 = 0.001$; Condition*rTMS: $F_{(1,35)} = 1.91$, $p = 0.18$, $\eta^2 = 0.05$; Language*rTMS: $F_{(1,35)} = 0.04$, $p = 0.84$, $\eta^2 = 0.001$) and three-way interaction (Condition*Language *rTMS: $F_{(1,35)} = 0.18$, $p = 0.68$, $\eta^2 = 0.005$) effects were non-significant.

Table 3.

Descriptive Statistics of Accuracy for Total Sample

Condition	Language	rTMS	Mean	SD	N
Control (sham-rTMS)	L1	Pre	18.67	2.849	36
		Post	19.94	3.004	36
	L2	Pre	13.97	3.605	36
		Post	15.75	4.576	36
Experimental (real-rTMS)	L1	Pre	19.39	3.532	36
		Post	20.08	2.999	36
	L2	Pre	14.97	3.692	36
		Post	15.36	3.208	36

Note: rTMS = repetitive transcranial magnetic stimulation; SD = standard deviation; N = number of participants.

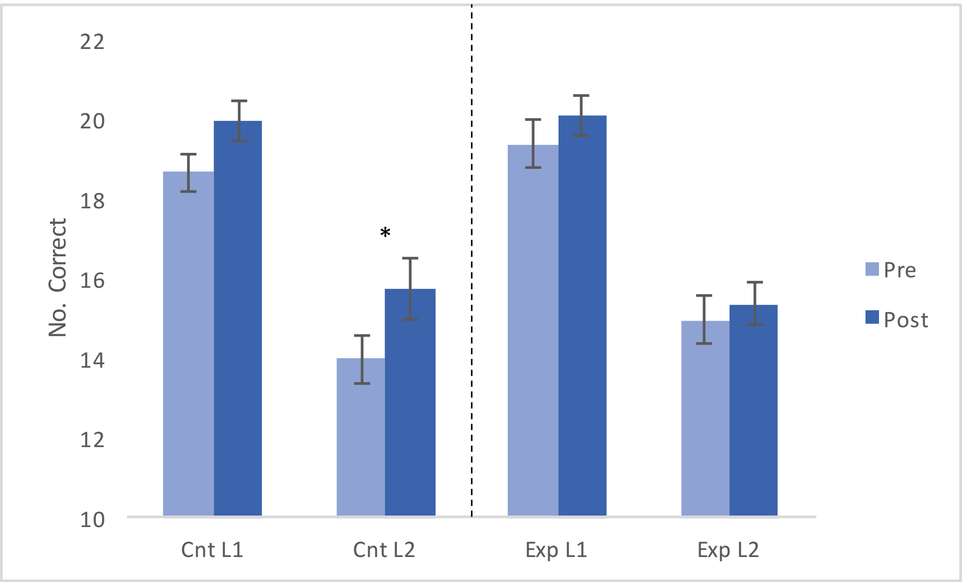

Figure 9. Mean (±SEM) accuracy on behavioral task. L1 = native language; L2 = second language; Cnt = control; Exp = experimental. *p<0.05.

Because the inter-individual variability of the rTMS effect may have masked the behavioral consequences of M1 stimulation, accuracy data were separated into responder (inhibitory) and non-responder (facilitatory) groups based on the effect of rTMS on MEP area.

Accuracy scores for the *inhibitory* group (n = 13) are presented on Table 4. The three-way rmANOVA revealed a significant main effect of language ($F_{(1,12)} = 30.85$, $p < .001$, $\eta^2 = 0.71$), explained by a higher accuracy in L1 compared to L2 in all conditions. No significant main effect was found for rTMS ($F_{(1,12)} = 3.44$, $p = 0.09$, $\eta^2 = 0.22$), or experimental condition ($F_{(1,12)} = 2.46$, $p = 0.36$, $\eta^2 = 0.03$), nevertheless, an interesting pattern of rTMS effects was observed in L2: in the control condition (sham-rTMS), L2 accuracy increased after the intervention, whereas in the experimental condition (real-rTMS) accuracy decreased after the intervention (Figure 10). No significant main effect was found for two-way interactions (Condition*Language: $F_{(1,12)} = 0.012$, $p = 0.92$, $\eta^2 = 0.001$; Condition*rTMS: $F_{(1,12)} = 2.66$, $p = 0.13$, $\eta^2 = 0.18$; Language*rTMS: $F_{(1,12)} = 1.22$, $p = 0.29$, $\eta^2 = 0.09$) and three-way interaction (Condition*Language *rTMS: $F_{(1,12)} = 0.31$, $p = 0.59$, $\eta^2 = 0.03$) effects were observed.

Table 4.

Descriptive Statistics of Accuracy in Inhibitory Group

Condition	Language	rTMS	Mean	SD	N
Control (sham-rTMS)	L1	Pre	18.62	3.124	13
		Post	20.08	2.813	13
	L2	Pre	13.85	3.105	13
		Post	15.38	4.174	13
Experimental (real-rTMS)	L1	Pre	19.69	3.326	13
		Post	19.77	4.045	13
	L2	Pre	15.62	3.754	13
		Post	14.08	2.842	13

Note: rTMS = repetitive transcranial magnetic stimulation; SD = standard deviation; N = number of participants.

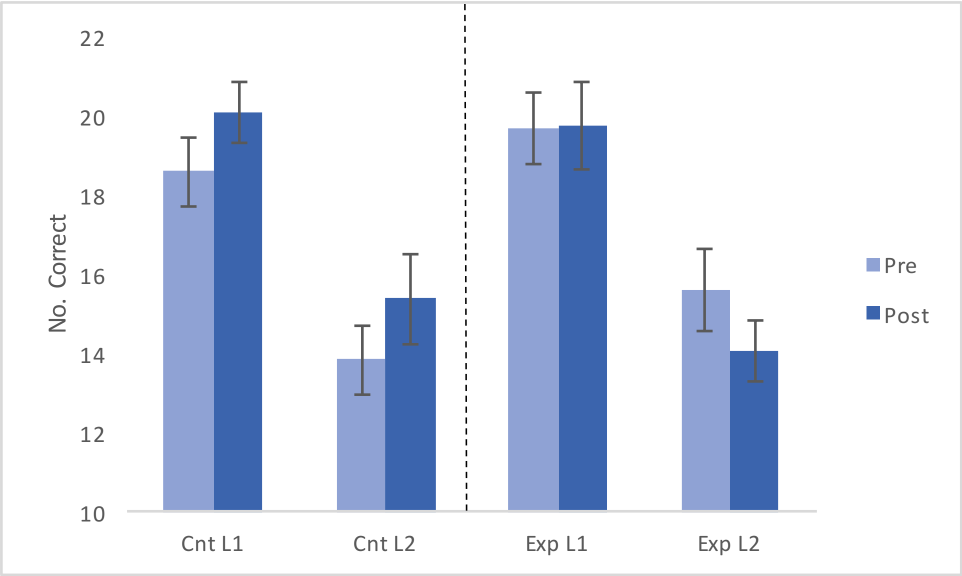

Figure 10. Mean (±SEM) accuracy on behavioral task for inhibitory group. L1 = native language; L2 = second language; Cnt = control; Exp = experimental.

Accuracy scores for the *facilitatory group* (n = 11) are presented on Table 5. The three-way rmANOVA revealed a significant main effect of language ($F_{(1,10)} = 20.05$, $p<.001$, $\eta^2 = 0.67$), and rTMS ($F_{(1,10)} = 18.62$, $p=.002$, $\eta^2 = 0.65$), but not of experimental condition (sham- vs. real-rTMS: $F_{(1,10)} = 0.15$, $p = 0.70$, $\eta^2 = 0.02$). The effect of language was explained by a higher accuracy in L1 compared to L2 in all conditions (Figure 11). The effect of rTMS shows that post-rTMS performance was more accurate than pre-rTMS, but the *post hoc t-tests* with Holm's sequential Bonferroni adjustment, showed non-significant differences for L1 in the control and experimental conditions ($t_{(10)} = -2.24$, $p = 0.05$, and $t_{(10)} = -0.73$, $p = 0.49$ respectively), and for L2 in the control and experimental conditions ($t_{(10)} = -0.77$, $p = 0.46$, and $t_{(10)} = -1.95$, $p = 0.08$ respectively). Expected two-way interaction (Condition*Language: $F_{(1,10)} = 0.007$, $p = 0.94$, $\eta^2 = 0.001$; Condition*rTMS: $F_{(1,10)} = 0.000$, $p = 1.0$, $\eta^2 = 0.00$; Language*rTMS: $F_{(1,10)} = 0.06$, $p = 0.81$, $\eta^2 = 0.006$) and three-way interaction (Condition*Language *rTMS: $F_{(1,10)} = 0.83$, $p = 0.38$, $\eta^2 = 0.8$) effects were non-significant (Figure 11).

Taken together, accuracy scores improved between trials, regardless of whether the intervening rTMS treatment was real or sham. Only those participants that showed an rTMS-induced reduction in MEP area (responders, or inhibitory) also showed a trend to decreased accuracy after rTMS for the L2; participants that showed an rTMS-induced increase in MEP area (non-responder, or facilitatory) showed the ***opposite*** trend. No apparent trend was observed in L1 accuracy.

Table 5.

Descriptive Statistics of Accuracy in Facilitatory Group

Condition	Language	rTMS	Mean	SD	N
Control	L1	Pre	18.09	2.66	11
(sham-rTMS)		Post	20.91	3.02	11
	L2	Pre	14.27	3.93	11
		Post	15.45	5.79	11
Experimental	L1	Pre	18.82	4.29	11
(real-rTMS)		Post	19.73	2.41	11
	L2	Pre	13	3.90	11
		Post	16.09	3.86	11

Note: rTMS = repetitive transcranial magnetic stimulation; SD = standard deviation; N = number of participants.

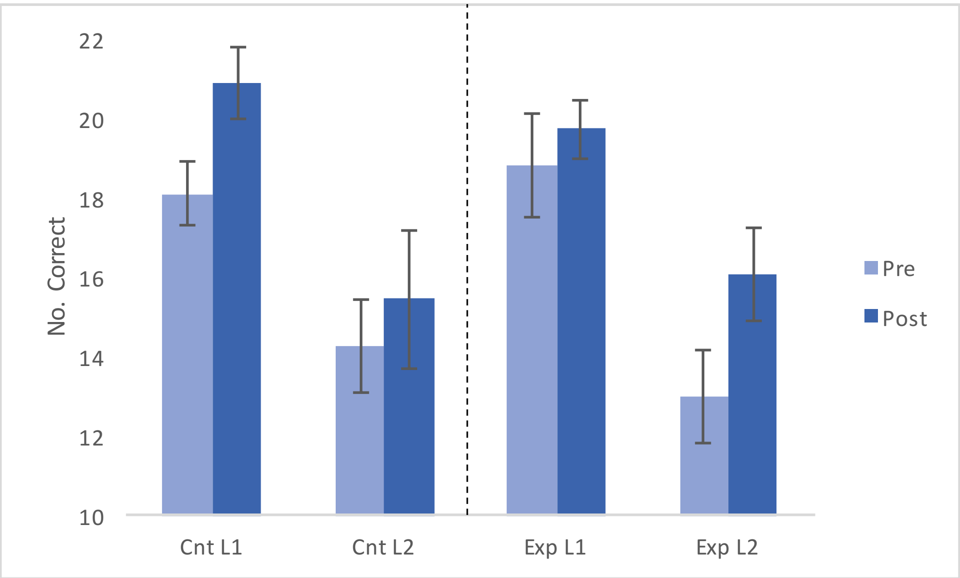

Figure 11. Mean (±SEM) accuracy on behavioral task for facilitatory group. L1 = native language; L2 = second language; Cnt = control; Exp = experimental.

Behavioral Task Reaction Times (RT)

Reaction times (RT) for correct responses in the total sample are presented on Table 6. The three-way rmANOVA revealed a significant main effect of language ($F_{(1,35)} = 33.13$, $p<.001$,

$\eta^2 = 0.49$), and rTMS ($F_{(1,35)} = 40.12$, $p<.001$, $\eta^2 = 0.53$), but not of experimental condition ($F_{(1,35)} = 1.78$, $p = 0.19$, $\eta^2 = 0.05$). The effect of language was explained by faster responses in L1 compared to L2 in all conditions. The effect of rTMS shows that post-rTMS performance was faster than pre-rTMS, (Figure 12); the *post hoc t-tests* using Holm's sequential Bonferroni adjustment, demonstrated differences for L1 and L2 in the control condition (sham-rTMS: $t_{(35)} = 3.65$, $p < 0.001$, $t_{(35)} = 4.03$, $p < 0.001$ respectively) but not for the experimental condition (real-rTMS: $t_{(35)} = 2.19$, $p = 0.03$, and $t_{(35)} = 1.42$, $p = 0.17$ respectively) indicating that, participants were faster when answering the task for the second time after sham-rTMS, but not after real-rTMS. The condition x rTMS interaction effect was significant ($F_{(1,35)} = 4.80$, $p = 0.04$, $\eta^2 = 0.12$), demonstrating faster responses after sham-rTMS than after real-rTMS. Other two-way interactions (Condition*Language: $F_{(1,35)} = 0.02$, $p = 0.90$, $\eta^2 = 0.00$; Language*rTMS: $F_{(1,35)} = 0.90$, $p = 0.35$, $\eta^2 = 0.03$) and three-way interaction (Condition*Language *rTMS: $F_{(1,35)} = 0.62$, $p = 0.44$, $\eta^2 = 0.02$) effects were non-significant.

Table 6.

Descriptive Statistics of Reaction Times for the Total Sample

Condition	Language	rTMS	Mean	SD	N
Control (sham-rTMS)	L1	Pre	2.429	0.712	36
		Post	2.041	0.532	36
	L2	Pre	3.191	1.116	36
		Post	2.573	0.791	36
Experimental (real-rTMS)	L1	Pre	2.164	0.723	36
		Post	1.965	0.634	36
	L2	Pre	2.802	0.954	36
		Post	2.589	1.008	36

Note: rTMS = repetitive transcranial magnetic stimulation; SD = standard deviation; N = number of participants.

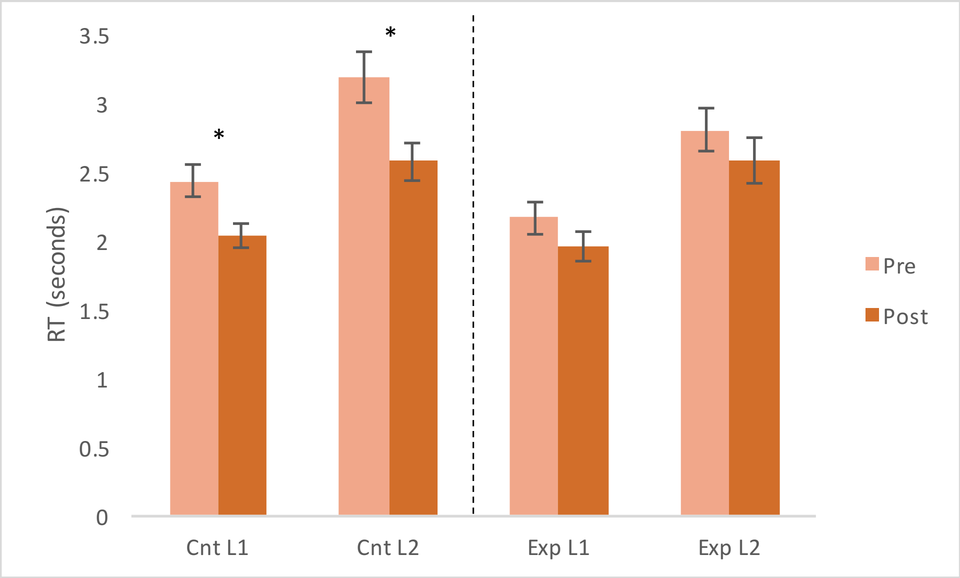

Figure 12. Mean (±SEM) median reaction time (RT) for the total sample. L1 = native language; L2 = second language; Cnt = control (sham-rTMS); Exp = experimental (real-rTMS). *p<0.05.

Because the inter-individual variability of the rTMS effect may have masked the behavioral consequences of M1 stimulation, RT data were separated into responders (inhibitory) and non-responder (facilitatory) groups based on the effect of rTMS on MEP area. RTs for the inhibitory group are presented on Table 7. The three-way rmANOVA revealed a significant main effect of language ($F_{(1,12)} = 15.50$, $p = 0.002$, $\eta^2 = 0.56$), and rTMS ($F_{(1,12)} = 28.61$, $p < .001$, $\eta^2 = 0.71$), but not of experimental condition ($F_{(1,12)} = 0.99$, $p = 0.34$, $\eta^2 = 0.08$). The effect of language was explained by faster responses in L1 compared to L2 in all conditions. The effect of rTMS shows that post-rTMS performance was faster than pre-rTMS; *post hoc t-tests* using Holm's sequential Bonferroni adjustment revealed a significant difference for L2 in the control (sham-rTMS) condition ($t_{(12)} = 3.82$, $p = 0.002$), but not in the experimental (real-rTMS) condition ($t_{(12)} = 0.77$, $p = 0.46$). No significant difference was found for L1 in the control or experimental condition ($t_{(12)} = 2.41$, $p = 0.03$, and $t_{(12)} = 1.28$, $p = 0.22$ respectively). The condition x rTMS interaction effect was significant ($F_{(1,12)} = 7.65$, $p = 0.02$, $\eta^2 = 0.39$), demonstrating faster responses after rTMS in the control condition than in the experimental condition. Other two-way interaction (Condition*Language: $F_{(1,12)} = 0.04$, $p = 0.84$, $\eta^2 = 0.004$; Language*rTMS: $F_{(1,12)} = 1.66$, $p = 0.22$,

$\eta^2 = 0.12$) and three-way interaction (Condition*Language *rTMS: $F_{(1,12)} = 1.22$, $p = 0.29$, $\eta^2 = 0.09$) effects were non-significant (Figure 13).

Table 7.

Descriptive Statistics of Reaction Time for Inhibitory Group

Condition	Language	rTMS	Mean	SD	N
Control (sham-rTMS)	L1	Pre	2.403	0.62	13
		Post	2.028	0.614	13
	L2	Pre	3.43	1.064	13
		Post	2.527	0.667	13
Experimental (real-rTMS)	L1	Pre	2.122	0.651	13
		Post	1.972	0.575	13
	L2	Pre	2.854	1.101	13
		Post	2.672	0.949	13

Note: rTMS = repetitive transcranial magnetic stimulation; SD = standard deviation; N = number of participants.

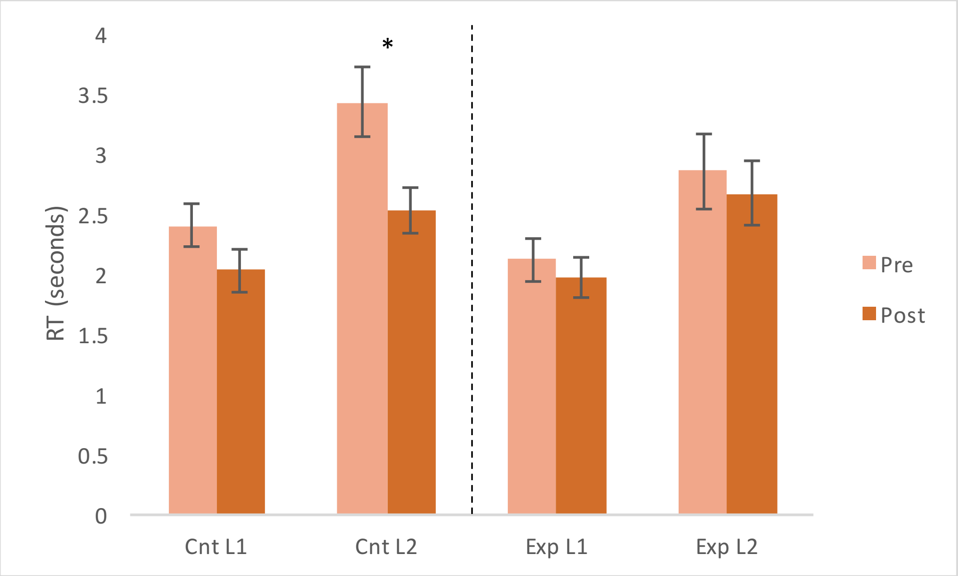

Figure 13. Mean (±SEM) median reaction time (RT) for the inhibitory group. L1 = native language; L2 = second language; Cnt = control; Exp = experimental. *p<0.05.

RTs for the facilitatory group are presented on Table 8. The three-way rmANOVA revealed a significant main effect of language ($F_{(1,10)} = 11.36$, $p = 0.007$, $\eta^2 = 0.53$), and rTMS ($F_{(1,10)} = 5.07$, $p = 0.048$, $\eta^2 = 0.34$), but not of experimental condition ($F_{(1,10)} = 0.76$, $p = 0.40$, $\eta^2 =$

0.07). The effect of language was explained by faster responses in L1 compared to L2 in all conditions. The effect of rTMS shows that post-rTMS performance was faster than pre-rTMS; *post hoc t-tests* using Holm's sequential Bonferroni adjustment showed no significant difference for L1 in the control (sham-rTMS) condition and experimental (real-rTMS) condition ($t_{(10)} = 1.37$, $p = 0.20$, and $t_{(10)} = 1.46$, $p = 0.18$ respectively), and for L2 in the control and experimental condition ($t_{(10)} = 0.50$, $p = 0.63$, and $t_{(10)} = 0.28$, $p = 0.79$ respectively). Two-way interaction (Condition*Language: $F_{(1,10)} = 1.07$, $p = 0.33$, $\eta^2 = 0.10$; Condition*rTMS: $F_{(1,10)} = 0.11$, $p = 0.75$, $\eta^2 = 0.01$; Language*rTMS: $F_{(1,10)} = 1.16$, $p = 0.31$, $\eta^2 = 0.10$) and three-way interaction (Condition*Language *rTMS: $F_{(1,10)} = 0.005$, $p = 0.94$, $\eta^2 = 0.001$) effects were non-significant (Figure 14).

Table 8.

Descriptive Statistics of Reaction Time in Facilitatory Group

Condition	Language	rTMS	Mean	SD	N
Control (sham-rTMS)	L1	Pre	2.252	0.76	11
		Post	1.912	0.29	11
	L2	Pre	2.892	1.22	11
		Post	2.723	0.86	11
Experimental (real-rTMS)	L1	Pre	2.08	0.58	11
		Post	1.831	0.59	11
	L2	Pre	2.522	0.69	11
		Post	2.479	1.11	11

Note: rTMS = repetitive transcranial magnetic stimulation; SD = standard deviation; N = number of participants.

In general, participants were faster in the post-rTMS trial, regardless of whether the intervening rTMS treatment was real or sham. However, rTMS moderated this effect, especially in the L2, in participants for whom rTMS also reduced the MEP area. For participants that showed an rTMS-induced increase in MEP area, no apparent trend was observed in RT.

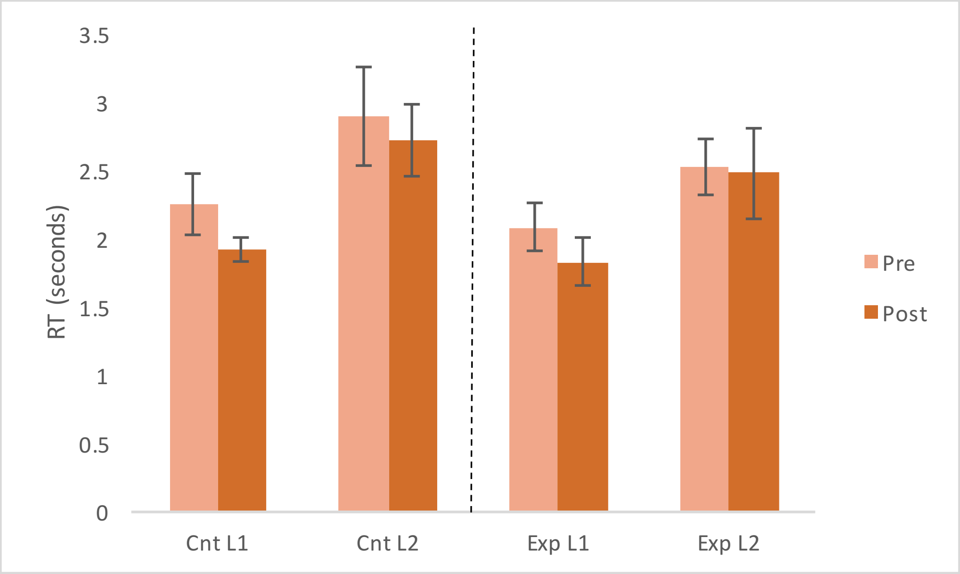

Figure 14. Mean (±SEM) median reaction time (RT) for the facilitatory group. L1 = native language; L2 = second language; Cnt = control; Exp = experimental.

Vowel Space Area (VSA)

For the 24 participants with reliable MEPs, three voice recordings (pre-rTMS, approximately 5- and 15-minutes post-rTMS) on L2, were analyzed to measure the VSA using an automated assessment (Berisha et al., 2017; Sandoval, Berisha, Utianski, Liss, & Spanias, 2013). Recordings from 2 participants were discarded due to sound quality. From the 22 remaining participants, 11 were identified as responders (inhibitory effect of rTMS) and 11 as non-responders (facilitatory effect of rTMS), based on the rTMS-induced effect on the MEP area (Table 9).

Table 9.

Group characteristics for Vowel Space Area analysis

Group	n	L2 Spanish	L2 English
Inhibitory	11	5	6
Facilitatory	11	2	9

Note: n = number of participants; L2 = second language.

VSA descriptive data for the *inhibitory* group are presented on Table 10. The one-way rmANOVA revealed no significant difference between the measures ($F_{(2,20)} = 1.52$, $p = 0.24$, $\eta^2 =$

0.13). However, the trend was in the expected direction, showing an important decrease 5 minutes after rTMS, and a slow recovery 15 minutes after the stimulation (Figure 15).

Table 10.

Descriptive Statistics of Vowel Space Area in the Inhibitory Group

Time	Mean	SD	N
Pre	191861	95252	11
Post ~5min	143503	60966	11
Post ~15min	172614	71727	11

Note: Pre = measure before repetitive transcranial magnetic stimulation (rTMS); Post ~5min = measure approximately 5-minutes after rTMS; Post ~15min = measure approximately 15-minutes after rTMS; SD = standard deviation; N = number of participants.

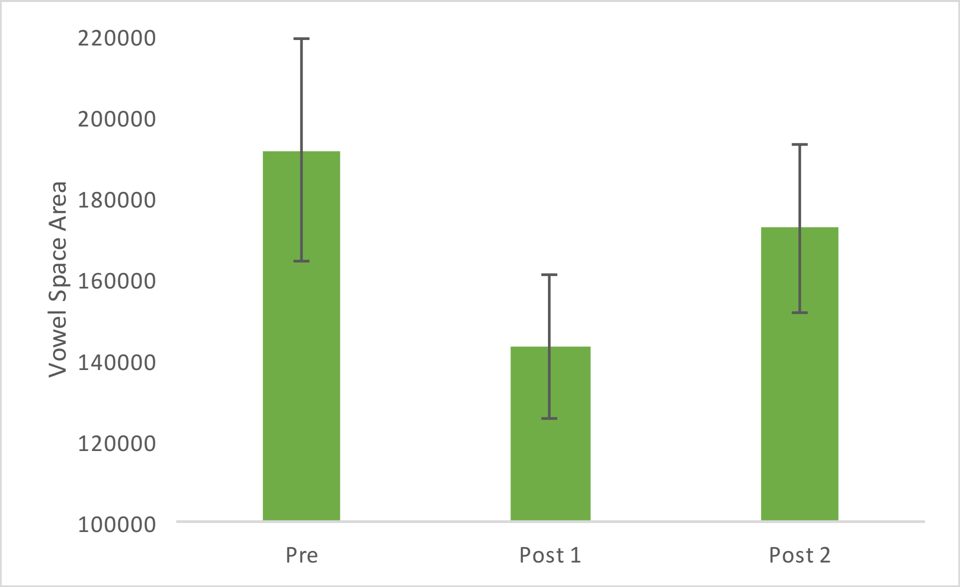

Figure 15. Vowel Space Area (VSA) change for the inhibitory group. Pre = measure before repetitive transcranial magnetic stimulation (rTMS); Post 1 = measure approximately 5 minutes after rTMS; Post 2 = measure approximately 15 minutes after rTMS.

VSA descriptive data for the *facilitatory* group are presented on Table 11. The one-way rmANOVA revealed no significant difference between the measures ($F_{(2,20)} = 1.28$, $p = 0.30$, $\eta^2 = 0.11$). Interestingly, the change between pre- and 5 minutes post-rTMS is small, and VSA is almost back to pre-rTMS levels after 15 minutes of the stimulation (Figure 16).

Table 11.

Descriptive Statistics of Vowel Space Area in the Facilitatory Group

Time	Mean	SD	N
Pre	109573	67197	11
Post ~5min	89441	60013	11
Post ~15min	104347	71490	11

Note: Pre = measure before repetitive transcranial magnetic stimulation (rTMS); Post ~5min = measure approximately 5-minutes after rTMS; Post ~15min = measure approximately 15-minutes after rTMS; SD = standard deviation; N = number of participants.

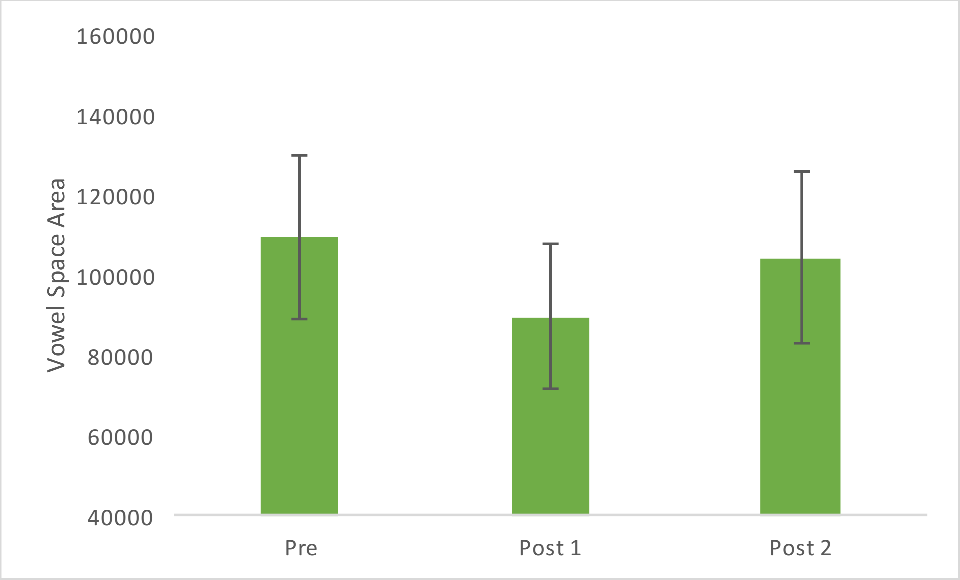

Figure 16. Vowel Space Area (VSA) change for the facilitatory group. Pre = measure before repetitive transcranial magnetic stimulation (rTMS); Post 1 = measure approximately 5 minutes after rTMS; Post 2 = measure approximately 15 minutes after rTMS.

Discussion

This study was conducted to evaluate the possible role of M1 in word recognition in L1 and L2. To this end, a low frequency rTMS protocol was used. The premise of the low frequency rTMS paradigm is the “virtual lesion” aftereffect (Möttönen & Watkins, 2012; Pascual-Leone et al., 2000; Walsh & Pascual-Leone, 2003); in other words, repetitive stimulation interferes with the neural function, resulting in inhibition of M1. Therefore, the hypothesis was that if M1 is recruited for word recognition under difficult conditions, more errors and longer reaction time in the experimental, as compared with sham conditions, should be observed for both L1 and L2; and because of less experience with L2, it should yield more errors and longer reaction times than L1 under both experimental and sham conditions.

The total sample data (n = 36) suggest a role of M1 in L2 word recognition, but not in L1. There was a significant accuracy improvement in L2 during the control condition, but this difference was minimal during the experimental condition. Additionally, participants were significantly faster in all post- intervention trials, but the change between pre- and post-rTMS was larger in the control than in the experimental condition, especially in L2. Thus, participants were faster and significantly more accurate in L2 after the sham- than after real-rTMS. In contrast, no effect was found for the L1, where accuracy and speed change between pre- and post-intervention was very similar in the control and experimental condition.

Findings in the total sample performance showed some support for the role of M1 on word recognition, especially for L2, but results were not conclusive because neither a significant main effect of condition (experimental vs. control), nor a two-way or three-way interaction effects were found. However, a detailed analysis of the MEP area change between pre- and post-rTMS revealed that the premise regarding the inhibitory influence of rTMS on M1 function only held for 54% of the participants. The other 46% actually exhibited a facilitatory aftereffect of rTMS on M1, as evidenced both by the increased size of their MEPs, and by the improvement in word recognition performance in L2. Previous research has reported similar variability on rTMS aftereffects, as well as a distribution of *responders* (those who show the expected effect after rTMS) and *non-responders* (those who do not show the expected response) close to 50%

(Jannati et al., 2017; Lopez-Alonso et al., 2014; Nettekoven et al., 2015; Strigaro et al., 2016). In the present study, evidence of enhanced MEPs, as well as enhanced word recognition for L2 was found, therefore we refer to the *non-responders* group as “*facilitatory*”, considering the possibility that the aftereffect has both physiological and functional consequences. Because behavioral results from the total sample included participants with opposite rTMS-induced physiological effects, total data interpretations could be misleading or biased. This could explain the small main effect of condition and the small interaction effects. Therefore, participants were divided into *responders* (inhibitory effect) and *non-responders* (facilitatory effect) groups for further behavioral data analysis.

In the ***responders*** (inhibitory) *group*, evidence of a motor role in speech word recognition in L2 was found. Participants were significantly slower and less accurate in L2 word recognition after rTMS, compared to the sham rTMS condition, where accuracy and speed improved. This result suggests that the rTMS-induced disruption of M1 associated with speech articulators interfered with L2 speech recognition. On the other hand, speed in L1 performance showed minimal change after rTMS-induced inhibition to M1, compared to the control situation. Although accuracy did not improve as much in the experimental condition as in the control situation, the improvement trend in both situations is evident, suggesting that the motor cortex during speech processing in this circumstance is not recruited. This is in line with previous research showing that the M1 role in speech processing is limited when speech perception is easy, but it is significant under challenging circumstances (Nuttall, Kennedy-Higgins, Devlin, & Adank, 2017; Stasenko et al., 2015). It is also consistent with research showing larger corticobulbar excitability in the OO muscle for perceptually and articulatory unfamiliar vowels (Schmitz et al., 2018). Apparently, the speech representation of high frequency words in L1 in the auditory system is highly accurate despite the noise, and no motor support was required for word recognition.

Evidence of a motor role in speech word recognition in the L2 was also found in the ***non-responders*** (facilitatory) group. Although MEP results from this group must be interpreted with caution due to the unexpected direction of the rTMS aftereffect, behavioral results showed an interesting trend. Accuracy in L2 improved after rTMS-induced facilitation, compared to a sham rTMS condition. Although this improvement in the facilitatory condition was significant only at the 0.1 level, the trend is important considering that reaction times in pre- and post-rTMS performance was very similar. Thus, a similar speed performance produced more accurate results for L2 after rTMS-induced facilitation. This is consistent with D'Ausilio et al. (2009) finding, that stimulating the motor representation controlling the articulator for a speech sound facilitates the perception of that sound. Also, Sato, Troille, Ménard, Cathiard, and Gracco (2013) showed that silently articulating a syllable in synchrony with the presentation of a concordant auditory ambiguous speech stimulus improves its identification. Accuracy and reaction times change between pre- and post-intervention in the *facilitatory* group for L1, was similar in the control and experimental condition. This finding is consistent with the result observed for L1 in the *inhibitory* group, where accuracy and reaction times change was also similar in the control and experimental condition. These suggest a role of M1 in L2 processing, but not in L1.

The results from the *inhibitory* and *facilitatory* groups provide substantial support for the role of M1 on L2 word recognition, and revealed a relation between physiological and functional consequences of rTMS. These findings support the hypothesis that auditory speech signals are transformed to motor models, which in turn affect sensory processing (Mottonen et al., 2014). This effect was observed mainly in the L2, suggesting a motor compensatory activation when acoustic-motor models are incomplete or lacking (Schmitz et al., 2018). Nevertheless, three-way interactions between experimental condition, language and, rTMS intervention were non-significant. This result could be the consequence of a learning effect of the task, or a small sample size. Faster responses during the post-intervention trials, regardless of the condition—real or sham rTMS—and the language, suggest a learning effect of the word-to-picture matching task. Each trial (pre- and post-intervention) included 114 words embedded in noise, and participants might have learned, during the initial stimuli presentations, to differentiate English and Spanish words based on minimal voice differences, develop strategies to answer more efficiently, or habituate to the noise and identify more easily the words. Additionally, from the total sample, data from 12 participants was discarded due to unreliable MEP measures, thus the group sizes were small, 13 and 11 for *inhibitory* and *facilitatory* groups respectively. This combination of factors may influence the statistical outcomes.

Inter-individual variability in rTMS aftereffects

From the total sample of 36 participants, MEP data from 12 participants were discarded. MEP data collection from the lip muscle is complicated and more difficult to obtain than MEP data from the FDI muscle. Because the coil is placed close to the face area, direct stimulation of facial nerves can produce a wave-form that could be wrongly interpreted as an MEP (Devlin & Watkins, 2007; Takenobu Murakami et al., 2011). Additionally, the production of lip-muscles MEPs is difficult compared to FDI MEPs because the M1 representation contributing to the hand is larger than for lips, the skull tends to be thicker over the lip area, and the corticobulbar motor pathway is shorter compared to the corticospinal pathway, producing a shorter onset latency (Adank et al., 2016), which can be problematic because the electrical pulses produce a signal that may overshadow the onset of lip MEP.

The results of the remaining 24 participants showed a 12% decrease of MEP size after rTMS, suggesting a M1 inhibitory effect. This result is congruent with the total behavioral performance that suggests a rTMS-induced inhibitory effect on L2. But the more interesting finding was that only 13 of the participants showed the expected inhibitory aftereffect, while 11 showed the opposite effect after rTMS. Similar variability in the low frequency rTMS aftereffect has been reported in the literature derived from studies targeting the FDI or other arm muscles in healthy participants (Fitzgerald et al., 2006; Houdayer et al., 2008; Jannati et al., 2017; Maeda et al., 2000), or stimulation to other brain regions related to cognitive or degenerative disease (Fitzgerald et al., 2006; M. T. Wilson & St George, 2016). Literature reporting this effect on the OO muscle is not available, and systematic studies on the aftereffects of rTMS on speech articulators (e.g. lip and tongue muscles) have not been conducted, revealing a gap in the scientific literature on language-related rTMS.

Individual differences including gender, brain anatomy, cognitive and motor function, age, attention, synaptic history, pharmacological influence, hormones, and genetics (Li et al., 2015; Ridding & Ziemann, 2010; L. M. Rogers & Dhaher, 2017), among others, are associated to the variability on MEP amplitude after low frequency rTMS. The exact mechanism through which rTMS induce an inhibitory or excitatory effect is, however, still under study. This project assigned participants to two groups based on the MEP aftereffect of rTMS. This measure was collected one time, during the experimental condition session. Considering the large variability on MEP change after real and sham rTMS, more than one real rTMS session is needed for a reliable measure of the aftereffect.

Theoretical Implications

Motor theories of speech perception argue that the listener's motor representations are necessary for processing speech sounds (Glenberg, 2015; Rizzolatti & Sinigaglia, 2015; S. M. Wilson, 2009). According to these theories, motor articulatory representations are recruited for optimal performance during speech processing because language evolved through an auditory-execution matching process, and therefore, there is a functional link between motor and perceptual representations of speech sounds (D'Ausilio et al., 2009; Takenobu Murakami et al., 2011). If motor articulatory representations are always recruited for speech perception, a temporary inhibition of M1 should produce less accurate and slower responses in L1 and L2. In this study only an effect on L2 was found, indicating a supporting effect of M1 under special circumstances like L2 processing, but no evidence of a role in L1 word recognition was found.

This study used background noise to increase the task difficulty. The signal-to-noise ratio (SNR) used was -2 db, which is considered an intermediate-to-weak noise level (Du et al., 2014; Lacross et al., 2016). The performance on the behavioral task revealed that participants were more accurate and faster in L1 than L2. This shows that, despite the easiness of the task and different proficiency levels among the participants, recognizing high frequency words embedded in noise was in general more challenging in L2 than L1. This result is consistent with Krizman, Bradlow, Lam, and Kraus' (2017) finding, that the speech-in-noise disadvantage observed in late learning bilinguals in their second language is also evident in highly proficient bilinguals and simultaneous language learners. Accordingly, the role of M1 was observed only during L2 word recognition. This result is in line with Nuttall, Kennedy-Higgins, Hogan, Devlin, and Adank (2016) finding, that the activation of the motor system increases with the difficulty of the perceptual task.

It gives additional support to neurocognitive models that argue that the activation of neurons within the speech motor programs facilitates their connection with sensory maps, supporting a top-down processing of the incoming stimuli that allows the activation of a production-base model of the input to support processing *only* under sub-optimal listening conditions (Adank, 2012; Devlin & Aydelott, 2009; Du et al., 2014; Nuttall et al., 2016; Sato et al., 2011; Stasenko et al., 2015; Van Engen & Peelle, 2014).

If M1 has a role in L2 word recognition as suggested by the results of this study, M1 should have an important role during the L2 acquisition process. When learning to articulate a speech sound, the ventral stream projecting to frontal motor regions may provide a mechanism to store sensory representations of speech and compare them against articulatory production. This comparison may improve future productions (Sato, Tremblay, & Gracco, 2009), as stronger motor programs would support speech perception through a top-down mechanism that helps disambiguate phonological information (Du et al., 2014; Tourville & Guenther, 2011). Previous research revealed that motor training for new phoneme production, and visual articulatory information and feedback (Kartushina et al., 2015; Navarra & Soto-Faraco, 2007; Schmitz et al., 2018; Zamuner et al., 2016), enhances speech comprehension. These findings support the hypothesis that L2 learning requires a stronger functional connectivity between articulatory-auditory and articulatory-orosensory brain regions to facilitate phonetic identification (Callan, Callan, & Jones, 2014; Callan, Jones, Callan, & Akahane-Yamada, 2004). However, other research has found that speech production training has no effect on speech comprehension, or may even have a negative impact on comprehension compared to perception-only training procedures (Baese-Berk & Samuel, 2016; Lu, Wayland, & Kaan, 2015). More research is needed to disambiguate the role of M1 during language acquisition, and the characteristics of the motor training that may support L2 production and comprehension.

Vowel Space Area (VSA) as a measure of rTMS aftereffect

The VSA for L2 was analyzed to determine its efficiency as a rTMS aftereffect measure. It was hypothesized that the VSA decreases after rTMS to M1 associated with speech articulators. Modulation of M1 was expected to affect VSA, and this effect was expected to dissipate as M1 recovers its original state. Results from the *inhibitory* group showed the predicted effect: VSA was smaller 5 minutes after rTMS to the lip-associated M1, compared to VSA before the stimulation. Fifteen minutes after rTMS to the lip-associated M1, VSA was larger than the post 5-minute measure, but smaller than the measure before the stimulation. This result suggests a slow recovery of the VSA associated with the rTMS aftereffect. Although the VSA difference between pre- and post-rTMS measures was not statistically significant, the trend direction is relevant (η^2 = 0.13) considering the small sample size (n = 11).

The *facilitatory* group showed a small change in VSA between pre-rTMS and 5 minutes post-rTMS. Additionally, 15 minutes post-rTMS, VSA returned to pre-rTMS levels. These results suggest that rTMS to the lip-associated M1 has a minimal aftereffect on VSA. Although the changes between pre- and post-rTMS were small, an unexpected trend was observed. The 5 minutes post-rTMS VSA was smaller than the pre-rTMS measure; an analogous trend was observed in the *inhibitory* group. If M1 stimulation is facilitatory of its activation, the VSA was expected to be the same or larger after rTMS. However, it is possible that fatigue played a role in post-rTMS VSA results. Participants were instructed to keep the head as still as possible during the 15-minute train of stimulation. They watched a cartoon without sound while rTMS was implemented, but several participants reported being sleepy immediately after the stimulation because of boredom. This may be a factor influencing VSA shortly after rTMS.

More data are required to draw precise conclusions on the efficiency of VSA as an outcome measure of low frequency rTMS. Although the *inhibitory* and *facilitatory* groups were small and no statistical significant differences were found between VSA measures pre- and post-rTMS, the trend observed is interesting and on the expected direction based on clinical observations of patients with dysarthria (Berisha et al., 2017; Skodda et al., 2012, 2011). This is, to our knowledge, the first study to use a speech measure like VSA to determine the aftereffect of low frequency rTMS in healthy subjects. This finding suggests new research lines on the relation between cerebral cortex activation (via rTMS) and speech measures like rate, stress, prosody, intelligibility, and goodness of pronunciation in the native and second language.

Future Directions

The purpose of using rTMS to modulate M1 and observe its behavioral aftereffects is to determine a causal relationship between M1 activation and speech comprehension. Although results from the present study strongly suggest that M1 has a role in L2 word recognition, it is not possible to establish a causal effect, as two- and three-way interactions between condition (real and sham brain stimulation), language, and pre- post-intervention effect, were not consistent or absent in this sample. To find more consistent results, a larger sample is necessary. Considering that approximately 50% of a typical sample are non-responders, and that lip MEP data is difficult to collect, a sample large enough to discard around 60% of the data, and still have enough subjects for optimal statistical power, is required. Additionally, more rTMS sessions are needed to determine with confidence the effect of rTMS on an individual. MEP-change variability was large, and differences between pre- and post-rTMS could be influenced by fatigue during the experimental session, difficulty in keeping the lips contracted, and a statistical regression to the mean effect. Running several rTMS sessions could rule out these unwanted effects, and give more reliable data on the direction and size of the rTMS aftereffect.

This study revealed a role of M1 in word recognition in L2, but little is known on what specific factors engage M1 support during speech perception. It could be the case that M1 helps disambiguating speech embedded in noise, and therefore manipulations of noise levels in L1 and L2 could show the level at which M1 supports speech comprehension. An alternative is that M1 enhances the perception of phonemic contrasts. In that case, studies comparing easy (L1 phonemes), difficult (L2 phonemes not present in L1) and trained (phonemes from an unknown language after motor and perceptual training) phoneme perception could give answers on the specific role of M1during speech perception. Additionally, the role of M1 could be associated to a semantic matter, where M1 supports comprehension of words with abstract, ambiguous, or unknown meaning to the individual. Thus, comparing different types of words in L1 and L2, while controlling for participants' proficiency, would give insight on M1 role on semantic processing.

It is evident that more research on low frequency rTMS effects on speech articulators like lips and tongue muscles is necessary. Because M1 areas associated to speech articulators and hand muscles are not anatomically identical, it is not possible to generalize rTMS effects on the FDI to other M1 associated muscles. Coil orientation, adequate muscle activation to establish the active motor threshold, duration of the aftereffects, characteristics of responders and non-responders, among other technical and physiological issues, need to be studied in order to successfully use rTMS as a tool for language research.

Conclusions

This study used rTMS to modulate the M1 associated to speech production, specifically to the lip (OO) muscle, during a bilingual (English/Spanish) word recognition task. Evidence of motor support to speech word recognition in the L2 was found. An inhibitory aftereffect of rTMS on M1 produced slower and less accurate responses in a word-to-picture matching task in L2. In line with this finding, a facilitatory aftereffect of rTMS on M1 produced more accurate responses in the L2 word recognition task. These results suggest an active role of the motor cortex in L2 speech recognition.

The aftereffect of a low frequency rTMS protocol to the lip muscle showed high inter-individual variability among a group of healthy individuals. Approximately 50% of the participants showed an inhibitory effect of rTMS, evidenced by smaller MEP area, while the other 50% had a facilitatory effect with bigger MEPs. This result suggests that rTMS may have a more complex influence on M1 excitability than is usually reported, therefore, relying only on grand-average results can obscure important inter-individual differences in rTMS physiological and functional responses within each group of participants.

An automatic assessment of L2 VSA was used to determine its efficacy as a measure of the aftereffect of low frequency rTMS. An *inhibitory* aftereffect of rTMS on M1 associated to speech articulators produced smaller VSA 5 minutes after the stimulation, and a slow recovery was observed after 15 minutes. A *facilitatory* aftereffect of rTMS on M1 produced limited changes in VSA 5 minutes after the stimulation, and VSA values went back to pre-rTMS levels after 15 minutes of the stimulation. These results suggest that speech measures may be indicative of the aftereffects of low frequency rTMS to M1 associated to speech production.

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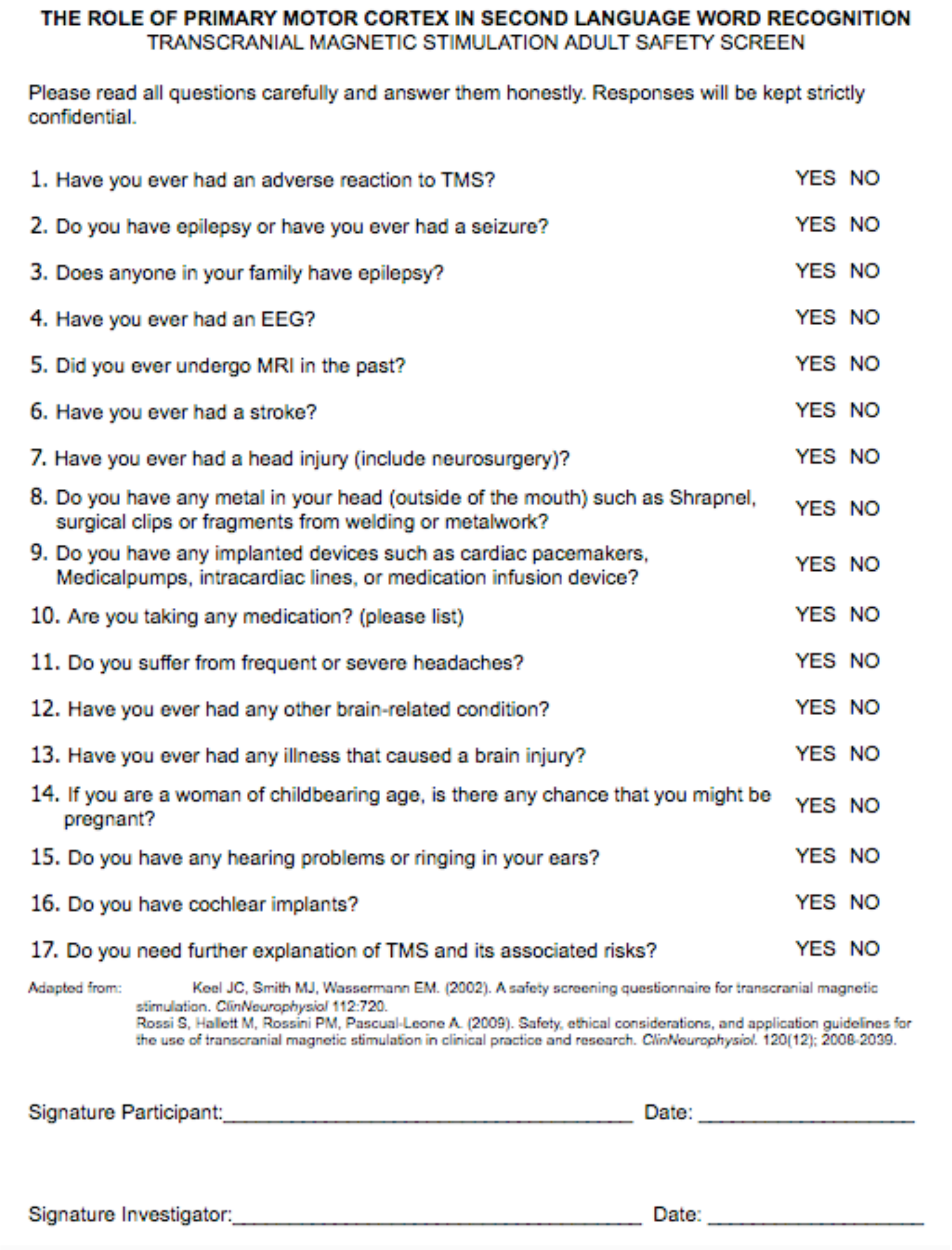
APPENDIX A

TMS SAFETY SCREENING QUESTIONNAIRE



THE ROLE OF PRIMARY MOTOR CORTEX IN SECOND LANGUAGE WORD RECOGNITION
TRANSCRANIAL MAGNETIC STIMULATION ADULT SAFETY SCREEN

Please read all questions carefully and answer them honestly. Responses will be kept strictly confidential.

1. Have you ever had an adverse reaction to TMS?	YES NO
2. Do you have epilepsy or have you ever had a seizure?	YES NO
3. Does anyone in your family have epilepsy?	YES NO
4. Have you ever had an EEG?	YES NO
5. Did you ever undergo MRI in the past?	YES NO
6. Have you ever had a stroke?	YES NO
7. Have you ever had a head injury (include neurosurgery)?	YES NO
8. Do you have any metal in your head (outside of the mouth) such as Shrapnel, surgical clips or fragments from welding or metalwork?	YES NO
9. Do you have any implanted devices such as cardiac pacemakers, Medicalpumps, intracardiac lines, or medication infusion device?	YES NO
10. Are you taking any medication? (please list)	YES NO
11. Do you suffer from frequent or severe headaches?	YES NO
12. Have you ever had any other brain-related condition?	YES NO
13. Have you ever had any illness that caused a brain injury?	YES NO
14. If you are a woman of childbearing age, is there any chance that you might be pregnant?	YES NO
15. Do you have any hearing problems or ringing in your ears?	YES NO
16. Do you have cochlear implants?	YES NO
17. Do you need further explanation of TMS and its associated risks?	YES NO

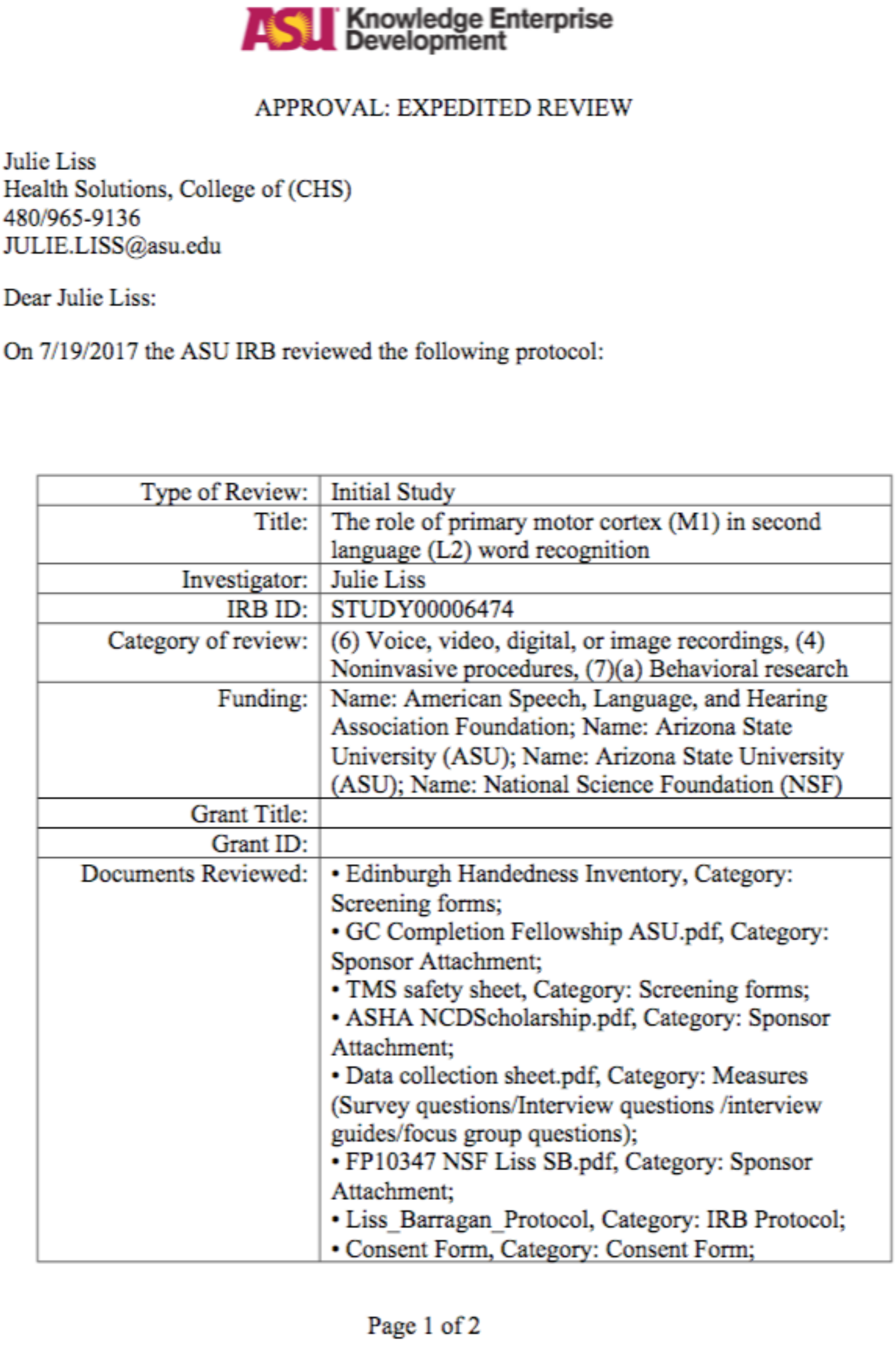
Adapted from: Keel JC, Smith MJ, Wassermann EM. (2002). A safety screening questionnaire for transcranial magnetic stimulation. *ClinNeurophysiol* 112:720.
Rossi S, Hallett M, Rossini PM, Pascual-Leone A. (2009). Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. *ClinNeurophysiol.* 120(12); 2008-2039.

Signature Participant:______________________________ Date: ________________

Signature Investigator:______________________________ Date: ________________

APPENDIX B

ARIZONA STATE UNIVERSITY INSTITUTIONAL REVIEW BOARD APPROVAL



ASU Knowledge Enterprise Development

APPROVAL: EXPEDITED REVIEW

Julie Liss
Health Solutions, College of (CHS)
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Dear Julie Liss:

On 7/19/2017 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	The role of primary motor cortex (M1) in second language (L2) word recognition
Investigator:	Julie Liss
IRB ID:	STUDY00006474
Category of review:	(6) Voice, video, digital, or image recordings, (4) Noninvasive procedures, (7)(a) Behavioral research
Funding:	Name: American Speech, Language, and Hearing Association Foundation; Name: Arizona State University (ASU); Name: Arizona State University (ASU); Name: National Science Foundation (NSF)
Grant Title:	
Grant ID:	
Documents Reviewed:	• Edinburgh Handedness Inventory, Category: Screening forms; • GC Completion Fellowship ASU.pdf, Category: Sponsor Attachment; • TMS safety sheet, Category: Screening forms; • ASHA NCDScholarship.pdf, Category: Sponsor Attachment; • Data collection sheet.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • FP10347 NSF Liss SB.pdf, Category: Sponsor Attachment; • Liss_Barragan_Protocol, Category: IRB Protocol; • Consent Form, Category: Consent Form;

	• Emeritus Fellowship.pdf, Category: Sponsor Attachment; • Research Info sheet, Category: Recruitment Materials; • LEAP-Q2007.pdf, Category: Screening forms; • Flyer, Category: Recruitment Materials;

The IRB approved the protocol from 7/19/2017 to 7/21/2018 inclusive. Three weeks before 7/21/2018 you are to submit a completed Continuing Review application and required attachments to request continuing approval or closure.

If continuing review approval is not granted before the expiration date of 7/21/2018 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Beatriz Barragan
Beatriz Barragan
Marco Santello
Kazumasa UEHARA

APPENDIX C

EXPERIMENTAL STIMULI WORDS

English		**Spanish**	
bad	bed	año	baño
band	sand	arma	alma
bees	cheese	baja	vaca
bell	hell	bala	sal
boat	vote	bar	mar
book	look	barco	banco
bug	rug	beso	peso
can	van	boca	loca
cap	cup	boda	moda
cat	cut	cabina	camina
dark	park	cama	cara
dirty	thirty	camino	casino
fall	ball	casa	caja
fun	fan	cola	copa
guess	gas	dado	dedo
light	right	elefante	elegante
lock	luck	foto	voto
mad	sad	fuego	juego
money	honey	fuente	puente
nurse	purse	fuerte	suerte
pain	rain	invierno	infierno
pan	man	mago	lago
pearl	girl	mono	mano
pen	pin	muerto	puerto
pet	jet	ocho	hoyo
pie	tie	ola	hora

pork	fork	palo	pelo
race	face	papa	tapa
sea	tea	ropa	rosa
three	tree	rubia	lluvia
toy	boy	sal	sol
watch	wash	via	dia

APPENDIX D

LANGUAGE EXPERIENCE AND PROFICIENCY QUESTIONNAIRE (LEAP-Q)

Northwestern Bilingualism & Psycholinguistics Research Laboratory
Marian, Blumenfeld, & Kaushanskaya (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *Journal of Speech Language and Hearing Research, 50* (4), 940-967.
Adapted to pencil-and-paper version by Marilyn Logan

Language Experience and Proficiency Questionnaire (LEAP-Q)

Last name		First name		Today's Date	
Age		Date of Birth		Male ☐	Female ☐

(1) Please list all the languages you know **in order of dominance**:

1	2	3	4	5

(2) Please list all the languages you know **in order of acquisition** (your native language first):

1	2	3	4	5

(3) Please list what percentage of the time you are *currently* and *on average* exposed to each language.
(*Your percentages should add up to 100%*):

List language here:					
List percentage here:					

(4) When choosing to read a text available in all your languages, in what percentage of cases would you choose to read it in each of your languages? Assume that the original was written in another language, which is unknown to you. (*Your percentages should add up to 100%*):

List language here:					
List percentage here:					

(5) When choosing a language to speak with a person who is equally fluent in all your languages, what percentage of time would you choose to speak each language? Please report percent of total time.
(*Your percentages should add up to 100%*):

List language here					
List percentage here:					

(6) Please name the cultures with which you identify. On a scale from zero to ten, please rate the extent to which you identify with each culture. (Examples of possible cultures include US-American, Chinese, Jewish-Orthodox, etc.):

Culture: _______________

0	1	2	3	4	5	6	7	8	9	10
No identification					Moderate identification					Complete identification

(7) How many years of formal education do you have? ________________________________

Please check your highest education level (or the approximate US equivalent to a degree obtained in another country):

☐ Less than High School
☐ High School
☐ Professional Training
☐ Some College
☐ College
☐ Some Graduate School
☐ Masters
☐ Ph.D./M.D./J.D.
☐ Other:

(8) Date of immigration to the USA, if applicable ____

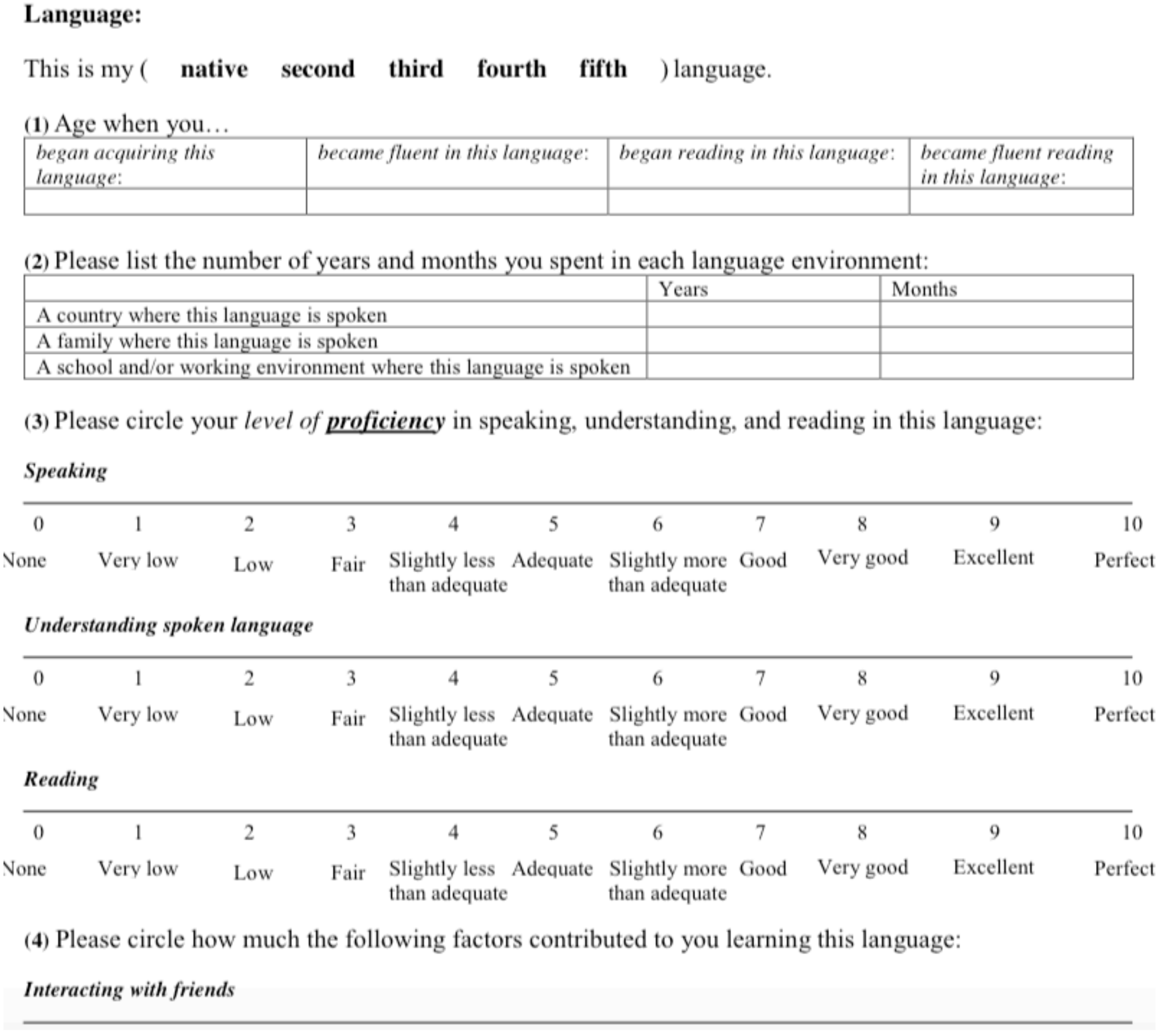
If you have ever immigrated to another country, please provide name of country and date of immigration here.

____

(9) Have you ever had a vision problem☐, hearing impairment☐, language disability☐, or learning disability ☐? (Check all applicable).

If yes, please explain (including any corrections):

____



Language:

This is my (**native** **second** **third** **fourth** **fifth**) language.

(1) Age when you…

began acquiring this language:	*became fluent in this language*:	*began reading in this language*:	*became fluent reading in this language*:

(2) Please list the number of years and months you spent in each language environment:

	Years	Months
A country where this language is spoken		
A family where this language is spoken		
A school and/or working environment where this language is spoken		

(3) Please circle your *level of* ***proficiency*** in speaking, understanding, and reading in this language:

Speaking

0	1	2	3	4	5	6	7	8	9	10
None	Very low	Low	Fair	Slightly less than adequate	Adequate	Slightly more than adequate	Good	Very good	Excellent	Perfect

Understanding spoken language

0	1	2	3	4	5	6	7	8	9	10
None	Very low	Low	Fair	Slightly less than adequate	Adequate	Slightly more than adequate	Good	Very good	Excellent	Perfect

Reading

0	1	2	3	4	5	6	7	8	9	10
None	Very low	Low	Fair	Slightly less than adequate	Adequate	Slightly more than adequate	Good	Very good	Excellent	Perfect

(4) Please circle how much the following factors contributed to you learning this language:

Interacting with friends

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

Interacting with family

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

Reading

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

Language tapes/self-instruction

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

Watching TV

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

Listening to the radio

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

(5) Please circle to what extent you are currently exposed to this language in the following contexts:

Interacting with friends

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

Interacting with family

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

Watching TV

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

Listening to radio/music

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

Reading

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

Language-lab/self-instruction

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

(6) In your perception, how much of a foreign accent do you have in this language?

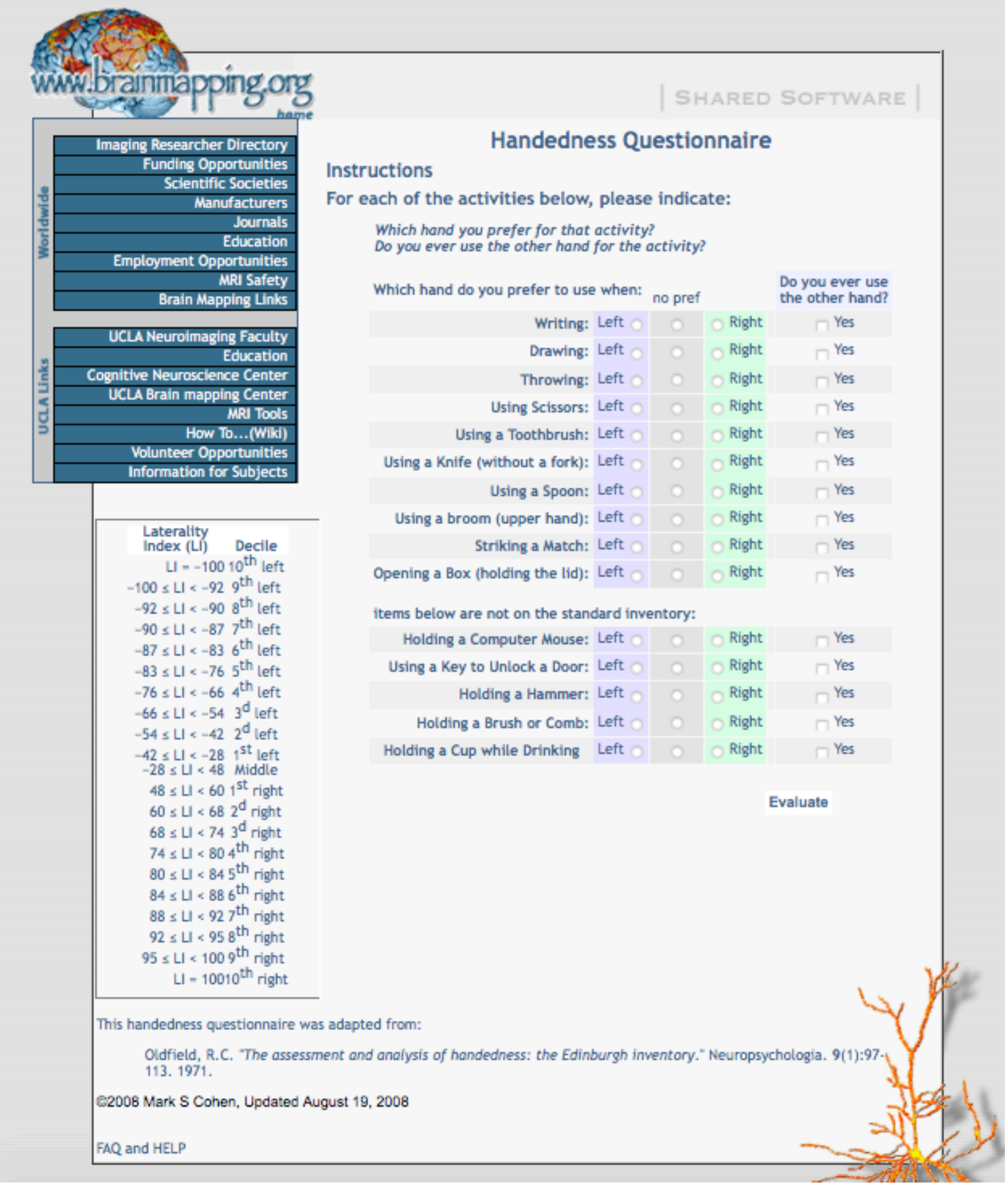
0	1	2	3	4	5	6	7	8	9	10
None	Almost none	Very light	Light	Some	Moderate	Considerable	Heavy	Very heavy	Extremely heavy	Pervasive

(7) Please circle how frequently others identify you as a non-native speaker based on your <u>accent</u> in this language:

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

APPENDIX E

EDINBURGH HANDEDNESS INVENTORY



Handedness Questionnaire

Instructions

For each of the activities below, please indicate:

Which hand you prefer for that activity?
Do you ever use the other hand for the activity?

Which hand do you prefer to use when:		no pref		Do you ever use the other hand?
Writing:	Left ○	○	○ Right	☐ Yes
Drawing:	Left ○	○	○ Right	☐ Yes
Throwing:	Left ○	○	○ Right	☐ Yes
Using Scissors:	Left ○	○	○ Right	☐ Yes
Using a Toothbrush:	Left ○	○	○ Right	☐ Yes
Using a Knife (without a fork):	Left ○	○	○ Right	☐ Yes
Using a Spoon:	Left ○	○	○ Right	☐ Yes
Using a broom (upper hand):	Left ○	○	○ Right	☐ Yes
Striking a Match:	Left ○	○	○ Right	☐ Yes
Opening a Box (holding the lid):	Left ○	○	○ Right	☐ Yes

items below are not on the standard inventory:

Holding a Computer Mouse:	Left ○	○	○ Right	☐ Yes
Using a Key to Unlock a Door:	Left ○	○	○ Right	☐ Yes
Holding a Hammer:	Left ○	○	○ Right	☐ Yes
Holding a Brush or Comb:	Left ○	○	○ Right	☐ Yes
Holding a Cup while Drinking	Left ○	○	○ Right	☐ Yes

Laterality Index (LI)	Decile
LI = −100	10th left
−100 ≤ LI < −92	9th left
−92 ≤ LI < −90	8th left
−90 ≤ LI < −87	7th left
−87 ≤ LI < −83	6th left
−83 ≤ LI < −76	5th left
−76 ≤ LI < −66	4th left
−66 ≤ LI < −54	3d left
−54 ≤ LI < −42	2d left
−42 ≤ LI < −28	1st left
−28 ≤ LI < 48	Middle
48 ≤ LI < 60	1st right
60 ≤ LI < 68	2d right
68 ≤ LI < 74	3d right
74 ≤ LI < 80	4th right
80 ≤ LI < 84	5th right
84 ≤ LI < 88	6th right
88 ≤ LI < 92	7th right
92 ≤ LI < 95	8th right
95 ≤ LI < 100	9th right
LI = 100	10th right

This handedness questionnaire was adapted from:

Oldfield, R.C. "*The assessment and analysis of handedness: the Edinburgh inventory.*" Neuropsychologia. 9(1):97-113. 1971.

FAQ and HELP

APPENDIX F

CONSENT FORM

CONSENT FORM

THE ROLE OF PRIMARY MOTOR CORTEX IN SECOND LANGUAGE WORD RECOGNITION

INTRODUCTION

The purposes of this form are to provide you (as a prospective research study participant) information that may affect your decision as to whether or not to participate in this research and to record the consent of those who agree to be involved in the study.

RESEARCHERS

Julie Liss, Ph.D., Professor in the Department of Speech & Hearing Sciences, College of Health Solutions.
Beatriz Barragan, MA., MS., doctoral candidate in Speech and Hearing Science.
Kazumasa Uehara, Ph.D., postdoctoral fellow in the Neural Control of Movement Laboratory, School of Biological and Health Systems Engineering.
Marco Santello, Ph.D., Professor in the School of Biological and Health Systems Engineering, Ira A. Foulton School of Engineering.

STUDY PURPOSE

The purpose of this project is to investigate the role of the motor cortex associated with speech production, in the comprehension of the native and the second language. We will use a noninvasive procedure called Repetititve Transcranial Magnetic Stimulation (rTMS), where a magnetic field is used to stimulate nerve cells in the brain. Specifically, we will stimulate nerve cells associated to the lip movement to examine its effect on word recognition in Spanish and English. The participants of this experiment are adult sequential bilingual (learned the second language during or after adolescence) speakers of English and Spanish, right handed, with no history of neurological or psychiatric illness, no implanted devices in the body, with minimal experience with other languages different from Spanish and English, and with no musical professional training. This project seeks to better understand the brain mechanisms underlying the comprehension of a second language, and contribute to the body of literature on neurophysiological processes involved in second language acquisition and comprehension.

DESCRIPTION OF RESEARCH STUDY

If you decide to participate, then you will join a study conducted in a collaboration between the Motor Speech Disorders Laboratory (MSDL) in the Speech and Hearing Science Department (Arizona State University; ASU), and the Neural Control of Movement Laboratory (NCML) in the School of Biological and Health Systems Engineering (ASU), involving the perception of a second language.

Your participation will consist of two sessions, one week apart. Both sessions will take place at the NCML, in the Physical Education Building East (PEBE) 171 at ASU, Tempe campus. If you agree to participate, you will sit upright and relaxed in front of a computer screen, on a confortable chair with the head supported by a headrest. During these sessions, you will perform on a word-to-picture matching task, where you will hear through headphones a word in English or Spanish, and then you will choose from 4 pictures on the screen, the one that best describes the word you heard. You will hear 224 words in 4 blocks of 56 words each, with a resting period of 15 seconds between blocks.

Following the word-to-picture matching task, we will use a technique called repetitive transcranial magnetic stimulation (rTMS). This technique involves passing a brief magnetic pulse over your skull to stimulate the nerve cells in the brain area associated with the lips movement. This stimulation will cause the muscle around your lips to make very small contractions. The brain stimulation will last 15 minutes. To measure the electrical activity of your lip muscles, we will use electromyography (EMG). For the EMG, the skin over your upper lip will be cleaned, and a small surface electrode will be attached using hypoallergenic medical tape. The electrode is attached by wires to a computer that records the electrical activity of the muscle. The electrical activity in the lip muscle is shown as a wavy line on the computer screen. After the rTMS procedure you will perform again on a word-to-picture matching task.

The second session will take place one week after the first, and will follow exactly the same procedure described for the first session. Each session will last no longer than 1 hour and 15 minutes.

RISKS

TMS methods carry minimal safety risks. Some people report discomfort on their scalp muscles, and/or a headache could come and go after the procedure, though both of these issues are less of a problem in the particular scalp areas we will be stimulating. If you report discomfort or headache the procedure will be immediately interrupted. rTMS has a very small chance of seizure induction. In the rare event of a seizure, the Epilepsy Society First Aid plan will be followed to keep the person safe; ASU health services and/or 911 will be immediately contacted. Possible effects on hearing have been described, therefore you will be asked to wear earplugs during TMS to avoid this possibility. While no current evidence is available which suggests TMS may be damaging to fetus, pregnant females will not be included in the study. There are no other risks from taking part in this study, but in any research, there is some possibility that you may be subject to risks that have not yet been identified.

BENEFITS

Although you will not benefit individually from participation in the research, this study will help us to understand the cognitive and neural mechanisms underlying the comprehension of second language speech. Results will contribute to the ongoing scientific debate on the role of motor brain regions during effortful speech listening, and will provide methodological guidance to subsequent research using TMS to study second language speech perception.

NEW INFORMATION

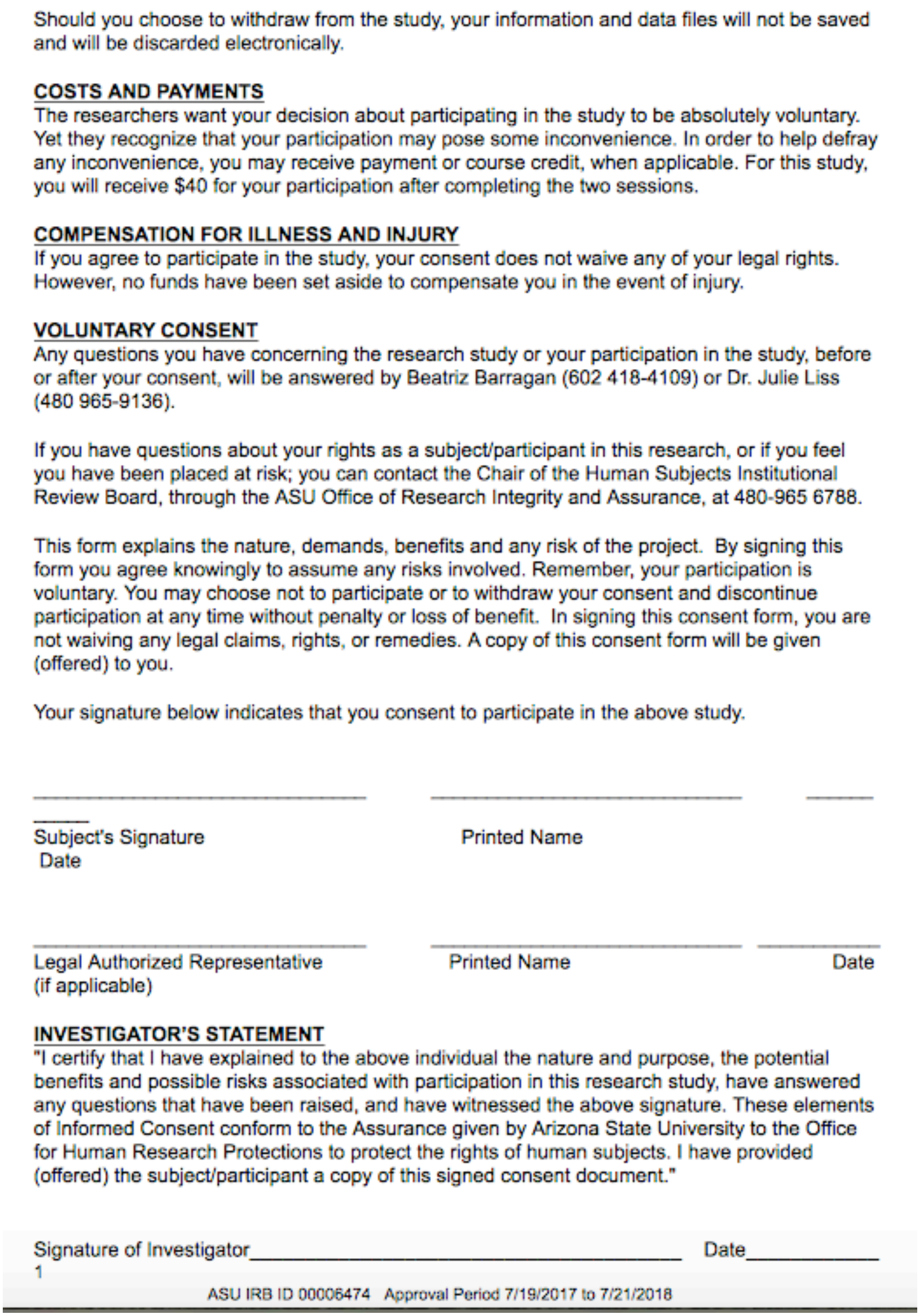
If the researchers find new information during the study that would reasonably change your decision about participating, they will provide this information to you.

CONFIDENTIALITY

All information obtained in this study is strictly confidential unless disclosure is required by law. The results of this research study may be used in reports, presentations, and publications, but the researchers will not identify you. In order to maintain confidentiality of your records, Beatriz Barragan will code all of your information so your identity cannot be determined from any of the data. The key to the code is kept in a separate location from the data and the data are locked in a cabinet. Only Beatriz Barragan and Dr. Julie Liss will have access to both the codes and the code key.

WITHDRAWAL PRIVILEGE

Your participation in this project is completely voluntary. There is no penalty for not participating, or for choosing to withdraw from participation at any time. Your decision will in no way affect your relationship with Arizona State University or your grade in any course.



Should you choose to withdraw from the study, your information and data files will not be saved and will be discarded electronically.

COSTS AND PAYMENTS

The researchers want your decision about participating in the study to be absolutely voluntary. Yet they recognize that your participation may pose some inconvenience. In order to help defray any inconvenience, you may receive payment or course credit, when applicable. For this study, you will receive $40 for your participation after completing the two sessions.

COMPENSATION FOR ILLNESS AND INJURY

If you agree to participate in the study, your consent does not waive any of your legal rights. However, no funds have been set aside to compensate you in the event of injury.

VOLUNTARY CONSENT

Any questions you have concerning the research study or your participation in the study, before or after your consent, will be answered by Beatriz Barragan (602 418-4109) or Dr. Julie Liss (480 965-9136).

If you have questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk; you can contact the Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at 480-965 6788.

This form explains the nature, demands, benefits and any risk of the project. By signing this form you agree knowingly to assume any risks involved. Remember, your participation is voluntary. You may choose not to participate or to withdraw your consent and discontinue participation at any time without penalty or loss of benefit. In signing this consent form, you are not waiving any legal claims, rights, or remedies. A copy of this consent form will be given (offered) to you.

Your signature below indicates that you consent to participate in the above study.

______________________________ ____________________________ ______
_____
Subject's Signature Printed Name
Date

______________________________ ____________________________ ___________
Legal Authorized Representative Printed Name Date
(if applicable)

INVESTIGATOR'S STATEMENT

"I certify that I have explained to the above individual the nature and purpose, the potential benefits and possible risks associated with participation in this research study, have answered any questions that have been raised, and have witnessed the above signature. These elements of Informed Consent conform to the Assurance given by Arizona State University to the Office for Human Research Protections to protect the rights of human subjects. I have provided (offered) the subject/participant a copy of this signed consent document."

Signature of Investigator______________________________________ Date___________

APPENDIX G

PASSAGES FOR ENGLISH AND SPANISH VOICE RECORDINGS

In a garden, there lived an ant and a grasshopper who were very good friends. It was springtime and the grasshopper was having a lot of fun playing, singing, and dancing in the sun. But the ant was hardworking. It was collecting food grains and storing them in its house. The grasshopper did not understand why the ant was doing so and said, "Hey,' Ant! Why don't you come outside and play with me?" The ant replied, "I cannot. I am storing food for the winter when there won't be anything to eat!" The grasshopper only laughed at the ant and said, "Why are you worrying now? There is plenty of food!" and continued to play, while the ant worked hard. When winter came, the grasshopper did not find a single grain of food to eat. It began to starve and feel very weak. The grasshopper saw how the hardworking ant had plenty of food to eat and realized its foolishness.

¿Te gustan los parques de atracciones? Bueno, a mí me encantan. Para divertirme, fui dos veces la primavera pasada. Mi recuerdo favorito fue cuando me subí a la oruga, que es una montaña rusa gigante muy alta. Cuando vi cómo la oruga se alzaba hacia el brillante cielo azul, supe que tenía que subirme. Después de hacer cola media hora, llegué a la entrada, donde había un hombre que te medía la altura para ver si me iba a poder subir. Le di unas monedas, le pedí que me diera el cambio, y me subí de un salto. Taca, taca, taca, la oruga subía despacio por los rieles. Subió tan alto que podía ver el estacionamiento. ¡Qué miedo! Pensé "Ahora no hay vuelta atrás." La gente tenía tanto miedo que gritaban al deslizarnos rápida y velozmente por los rieles. Tan rápidamente como había empezado, la oruga se detuvo. Desafortunadamente, era ya la hora de subirse al coche e ir a casa. Aquella noche soñé con el viaje tan emocionante en la oruga. ¡Mi recuerdo más memorable es haber ido al parque de atracciones y haberme subido a la oruga!