Is word-level lexical stress sensitivity affected by downregulation to the left superior temporal gyrus using TMS?

Gareth J. Williams[1], Stacey A. Bedwell[2], Charlotte A. Boatman[1], & Suvobrata Mitra[1],

[1]Nottingham Trent University

[2]Birmingham City University

Author Note

Gareth J. Williams, Department of Psychology, Nottingham Trent University; Stacey Bedwell, Department of Psychology, Birmingham City University; Suvo Mitra, Department of Psychology, Nottingham Trent University; Charlotte Boatman, Department of Psychology, Nottingham Trent University. Correspondence concerning this article should be addressed to Gareth. J. Williams, Department of Psychology, Nottingham Trent University, 50 Shakespeare Street, Nottingham, NG1 4FQ. E-mail: gareth.williams@ntu.ac.uk. Telephone: +44 (0)115 848 4125.

Abstract

This paper reports two experiments using Transcranial Magnetic Stimulation (TMS) to investigate whether word-level lexical stress involves the left superior temporal gyrus (STG) using a grammar classification task designed to elicit a typicality effect. Experiment 1 used text presented stimuli and, although was not able to elicit a typicality effect, found response times were significantly slower in the no TMS condition compared to when the, control, right PAR region was downregulated. In Experiment 2, speech was presented instead of text and accuracy and response times were similar across all three conditions. A lexical decision control task found evidence, from response time analysis, that the left STG and the right PAR were involved in word and nonword judgments. The discussion explores the findings relative to lexical stress and the role of cortical regions in word and response processing.

Keywords: *lexical stress, prosody, word-level, speech, TMS*

1 Introduction

Prosody is the pattern of acoustic emphases given to speech information. Spoken multisyllabic words tend to have a pattern of emphasis and de-emphasis across different syllables (Lieberman, 1960; Plag, Kunter, & Schramm, 2011). Within words, stressed syllables typically have an increase in acoustic energy around their vowels, whereas an unstressed syllable loses the sound of the vowel and becomes a, quieter and shortened, schwa sound (McClean & Tiffany, 1973). Typically, speakers are also observed to apply word prosody as they produce sentences. Moreover, there is a tendency for individuals reading aloud to apply prosodic patterns to text (Ferreira, 1993). In written English there are no explicit prosodic markers to guide the reader, although it is likely orthography plays a role (Kelly, 2004) as does recall of prosodic patterns from long term memory (Rastle & Coltheart, 2000). Although there has been considerable attention to the role of cognition in lexical stress (e.g. Arciuli & Cuppels 2003; Arciuli & Cuppels, 2004; Arciuli & Slowiaczek, 2007; Kelly, 2004; Rastle & Coltheart, 2000; Ševa, Monaghan, & Arciuli, 2009; Williams & Wood, 2012), there have been fewer studies of the cortical regions that are involved in processing word-level lexical stress patterns (Klein, Domahs, Grande, & Domahs, 2011; Belyk & Brown, 2014). The study reported here is the first Transcranial Magnetic Stimulation (TMS) study of a cortical region thought to be involved in word-level lexical stress.

Neuroimaging studies have identified a specific role for the left superior temporal gyrus (STG) in word-level lexical stress processing. Zatorre, Evals, Meyer, and Gjedde (1992) found activation in the left STG in a study where participants made judgements between pairs of spoken syllables that were manipulated for pitch. Klein, Domahs, Grande, and Domahs' (2011) functional magnetic resonance imaging (fMRI) study found that the left STG was activated for some word stress judgments in Dutch but that both the left and right STG areas were activated when the judgments were more complicated. For example, the judgment of whether non-identical pairs of words were the same or different. Belyk and Brown (2014) identified that there was a difference in the locations of emotional compared with linguistic prosody. In their meta-analysis, they found that the perception of linguistic structural information tended to involve the lower part of the inferior frontal gyrus. Where there was overlap with the left STG it was in the processing of syntax and affect. The left STG has also been shown to be involved in the cortical network for processing semantic information from spoken sentences (Friederici, Rueschemeyer, Hahne, & Fiebach 2003; Leff *et al*., 2009), involved in verbal memory processing (Leff *et al*. 2009), and is associated with the cortical network in individuals who experience auditory spoken hallucinations (Plaze *et al.* 2006).

TMS offers the opportunity to complement neuroimaging studies and studies of patients with brain lesions (Papagno, Fogliata, Catricalà, & Miniussi, 2009). With TMS, a specific cortical region can be downregulated, and the behavioral outcomes of a task measured in an experimental paradigm (Kosslyn *et al.*, 1999). Therefore, TMS is an approach that can demonstrate whether the left STG is involved in lexical stress sensitivity, as indicated by Klein *et al.*'s (2011) neuroimaging study.

The approach used to measure lexical stress sensitivity behavioral outcomes was to exploit a property of the English language where the majority of two-syllable nouns and verbs have a typical lexical stress pattern (Ševa, Monaghan, & Arciuli, 2009). The typical pattern for nouns is strong-weak and the pattern for verbs is weak-strong. However, there are a minority of English words where the lexical stress pattern is reversed (Arciuli & Cuppels, 2003). This typicality effect, that there is a corpus of words with a typical lexical stress pattern for their grammar class, has been used to study lexical stress in English in Arciuli and Cuppels (2003) and Arciuli & Slowiaczek (2007). The use of typical and atypical words is based on the prediction that typical items are more likely to have more accurate and faster grammar classification responses (i.e. responses from participants when asked if a word presented is a noun or a verb) than atypical items. A prediction confirmed in the speeded grammar task used by Arciuli and Cuppels (2003) and in a dichotic listening task by Arciuli and Slowiaczek (2007), where – in the latter study – there was a left hemisphere dominance for lexical stress judgments.

There has been considerable debate about how lexical stress patterns are applied to nonwords and pseudowords (Mousikou, Sadat, Lucas, & Rastle, 2017). Given that readers are able to construct plausible lexical stress patterns to multisyllabic words that they have not encountered in the past, it follows that they are able to derive this from orthographic cues or rules learnt from print exposure (Kelly, 2004; Perry, Ziegler, & Zorzi, 2010; Rastle and Coltheart, 2000; Ševa, Monaghan, & Arciuli, 2009). However, there is convergent evidence that, for known words, lexical stress patterns are stored as part of a mental lexicon (Cutler & Norris, 1988; Rastle & Coltheart, 2000; Perry, Ziegler, & Zorzi, 2010; Ševa, Monaghan, & Arciuli, 2009).

It is possible that the use of TMS more broadly, instead of the downregulation of the left STG, affects behavioral responses for word-level lexical stress tasks. Therefore, an alternative cortical region, the right parietal (PAR) lobe, will also be used as a control location. Previous research indicated that the right hemisphere is less likely to be related to word-level lexical stress (George et al., 1996; Arciuli & Slowiaczek, 2007), having a role in sentence level lexical stress sensitivity. In Hoekert, Bais, Kahn, & Aleman (2008) their TMS stimulation of the right parietal operculum resulted in changes to behavioral responses to sentences with spoken emotional prosody. Notwithstanding the right parietal lobe's role in emotional processing, the region has also been found to be involved in numerical and conceptual processing but not the processing of object names (Cappelletti, Lee, Freeman, & Price, 2010).

It is also possible that the left STG is more generally associated with processing lexical information. Papagno et al. (2009), for example, found TMS pulses to the left STG affected behavioral responses to abstract words. Alternatively, the left STG might be involved in some form of decision-making general to all tasks involving judgement responses. Therefore, in addition to using the right PAR as a comparison location, a control task, lexical decision, was also designed. In the canonical lexical decision task, participants are required to make a judgement about whether a letter string presented is a real word or nonword. It has been well established that words have faster and more accurate response times than nonwords and that high frequency words have faster and more accurate responses than low frequency words (Scarborough, Cortese & Scarborough, 1977; Gardner, Rothkopf, Lapan, & Lafferty, 1987). Since the decision made in the task involves linguistic information (Coltheart, Besner, Jonasson & Davelaar, 1979) but does not require stress assignment information, the control task allows there to be a comparison as to whether the left STG is involved only in lexical stress sensitivity or whether this location affects general lexical processes. Where neuroanatomical studies of lexical decision have been carried out, Edwards, Pexman, Goodyear and Chambers (2005) identified activation in areas of the inferior frontal cortex.

Experiment 1 sought to address the following research question: To what extent is lexical stress sensitivity affected by downregulation of the left STG when items are presented as text? Two control conditions were used to compare the behavioral responses in the left STG condition. These were a condition without TMS and a condition where TMS pulses were applied to the right PAR. Furthermore, participants were tested on an additional task that was not expected to be affected by downregulation of the left STG, a task that involved the assessment of linguistic information leading to a lexical decision.

2 Experiment 1

2.1 Participants

Twenty-one participants took part. It was necessary to exclude five participants from data analysis. Two participants had no recorded participant characteristics, two reported that English was their second language, and one reported having dyslexia. The remaining group (11 females and 5 males) had a mean age of 28 years (*SD* = 8.76). These 16 participants had English as their first language, no reported dyslexia, nor reported history of hearing difficulties. All participants were screened for exclusionary criteria in accordance with Rossi, Hallett, Rossini and Pascual-Leone (2009) and reported having normal or corrected-to-normal vision. A further five participants piloted the experimental method and materials without TMS. The participants were recruited through a panel maintained at Nottingham Trent University's (NTU) Department of Psychology and were paid £20 per 2-hour session. Ethical approval for the study was obtained from the College of Business, Law and Social Sciences Research Ethics Committee, Nottingham Trent University.

2.2 Experimental Tasks

2.2.1 Grammar classifications to nouns and verbs.

The word items were drawn from Arciuli and Slowiaczek (2007), an item list featured in Arciuli and Cuppels (2004) and drawn, mainly from a – larger – item list in Arciuli and Cuppels (2003). The word list comprised 40 nouns and verbs that either had a typical lexical stress (HAL word frequency *mean* = 15,833.05, *SD* = 19,231.21, *n* = 20) or an atypical lexical stress (HAL word frequency *mean* = 16,565.75, *SD* = 18,465.70, *n* = 20). The items were presented as black text, 24-point font with a courier typeface, on a white background at a distance comfortable to the participant. Participants were asked to classify, as quickly as possible, if the item they read was either a noun or a verb. Participants completed four practice items that were not task items. These gave feedback for response time, with guidance that responses should be faster than

2,000ms, and whether the response was correct or incorrect. The test trials provided no feedback and each item was presented twice in one test block.

2.2.2 Lexical decisions involving words and nonwords.

The lexical decision control task drew words and nonwords from the English Lexicon Project (Balota et al., 2007). Twenty, six-letter words were selected for the task. As the grammar classification task used two-syllable words, only two-syllable words were also selected for the task. The items had a word frequency (Hal) *mean* = 16,162.25 (*SD* = 1506.84). Twenty, six-letter non-words were also used as filler items (see Appendix A). Participants were asked to respond with one button if they saw a word and a different button if the letter string presented a nonword. When a participant read a word and they responded that this was a word, this was marked as correct; when they responded that it was a nonword, this was marked as incorrect. Where a participant read a nonword and they responded this was a non-word, this was marked as correct; when they responded it was a word, this was marked as incorrect. Participants received six practice trials, with guidance if their response time was longer that 2,000ms, and whether their response was correct or incorrect.

2.2.3 TMS setup, cortical location, and stimulation characteristics.

We administered rTMS prior to experimental trials using the Magstim (Whitland, UK) Rapid2 stimulator through a 70mm air film coil placed tangentially over the scalp. Participants sat in a Rogue Research TMS chair (Montreal, Canada) with the coil positioned by the chair's articulating support arm and manually steadied by the experimenter if needed. Prior to the experimental trials in the TMS conditions, participants received 10 minutes of 1 Hz rTMS (total 600 pulses) with the stimulator's output fixed at 60% of maximum capacity. The ANT Neuro Visor2 XT neuronavigation system (Enschede, Netherlands) was used to digitize a model of the participant's head and a standard MRI dataset was mapped to the model. Based on this mapping, the Talairach coordinates of stimulation sites for left superior temporal gyrus (x = -54, y = -21, z

= 10) and right parietal lobe (x = 24, y = -56, z = 54) were set (Figure 1). A minimum 10-minute interval separated the experimental conditions.

[Please insert Figure 1 about here]

2.2.4 Procedure

The experimental tasks were controlled by an OpenSesame script (Mathôt, Schreij, & Theeuwes, 2012). Participants completed the tasks in a quiet laboratory room with a researcher present. The order of the tasks and the rTMS conditions was counterbalanced by participant.

2.3 Results

One participant had substantively lower accuracy than the other participants in the STG grammar classification condition (z score below -2.5 SD). This participant was excluded from subsequent grammar classification analyses.

To analyse response time and accuracy the ‘lme4’ package (Bates, Mächler, Bolker, & Walker, 2015) was used in R (R Core Team, 2015), where accuracy was analysed using ‘glmer’ function with a binomial link and response time used the ‘lmer’ function. For accuracy and response time as dependent measures, the models included typicality and location as fixed effects and by-participant and by-items random intercepts. Tukey corrected comparisons were calculated using the ‘emmeans’ package (Length, 2019). The accuracy estimates are reported as log odds ratios.

2.3.1 Grammar classifications to nouns and verbs.

Once adjusted for multiple comparisons, in the no TMS condition the accuracy of typical items was similar to that of atypical items, $\beta = 0.35$, $SE = 0.14$, $p = 0.1$. This pattern was similar in both the left STG location, $\beta = 0.79$, $SE = 0.3$, $p = 0.99$, and the right PAR location, $\beta = 0.73$, $SE = 0.28$, $p = 0.96$.

For response times, only responses that were correct and slower than 150ms were included. This resulted in the removal of 274 (7.61%) datapoints. The pattern of response times was similar for typical and atypical items in the no TMS condition, $\beta = 16.76$, $SE = 24.97$, $p = 0.99$, the left STG location, $\beta = 3.34$, $SE = 25.01$, $p = 1$, and the right PAR location, $\beta = -5.21$, $SE = 25.01$, $p = 1$. There were two significant interactions; the right PAR location had significantly faster response times than the no TMS condition for typical items, $\beta = 40.44$, $SE = 13.94$, $p = 0.04$, and for atypical items, $\beta = 62.41$, $SE = 14.3$, $p < .001$.

[Please insert Figure 2 about here]

[Please insert Figure 3 about here]

2.3.2 Lexical Decisions involving words and nonwords.

A technical error resulted in the loss of data from one participant. Therefore, data from fifteen participants were available for analysis.

Following adjustment for multiple comparisons, accuracy was similar for words and nonwords in the no TMS condition, $\beta = 0.49$, $SE = 0.27$, $p = 0.79$, the left STG location, $\beta = 0.27$, $SE = 0.16$, $p = 0.21$, and the right PAR location, $\beta = 0.27$, $SE = 0.16$, $p = 0.21$. There were no statistically significant interactions.

For response time (correct-only trials with response times slower than 150ms), where word and nonword trials were compared within each of the no TMS, left STG, and right PAR conditions (67, 1.86%, data-points were removed), words were responded to significantly faster than nonwords for no TMS, $\beta = 60.78$, $SE = 14.07$, $p < .01$, left STG, $\beta = 45.33$, $SE = 14.08$, $p = 0.02$, and right PAR, $\beta = 40.61$, $SE = 14.08$, $p = 0.045$.

For word items, no TMS response times were significantly slower than left STG response times, $\beta = 35.71$, $SE = 10.01$, $p < .005$. For nonword items, the response times were larger between no TMS condition and the locations with TMS than between the left STG and right PAR locations, no TMS > left STG, $\beta = 51.15$, $SE = 10.1$, $p < .001$, no TMS > right PAR, $\beta = 30.5$, $SE = 10.1$, $p = 0.03$.

For interactions between the TMS conditions and the word or nonword conditions, there was a larger difference between the no TMS condition and the locations with TMS, no TMS nonword > left STG word, $\beta = 96.49$, $SE = 14.06$, $p < .001$, no TMS nonword > right PAR word, $\beta = 71.11$, $SE = 14.06$, $p < .001$, and for the comparison between both TMS locations, right PAR nonword > left STG word, $\beta = 65.99$, $SE = 14.08$, $p < .01$, than when either with-TMS nonword response times were compared to no TMS word response times or when the left STG nonword response times were compared with the right PAR word response times.

[Please insert Figure 4 about here]

[Please insert Figure 5 about here]

2.3.3 Summary of findings from Experiment 1

The results from the grammar classification experiment indicated that accuracy to typical and atypical words judgments were similar in the no TMS condition and in both conditions with TMS. For the lexical decision control task, words had a similar accuracy compared to nonwords in all three TMS conditions.

For response times, the grammar classification task was not able to elicit a typicality effect. However, the no TMS condition had significantly slower response times compared with the right PAR for both typical and atypical items. For lexical decision response times, words had significantly faster response times than nonwords. The no TMS condition generally had slower response times than conditions with TMS. For word items no TMS responses were significantly slower compared to the left STG condition and for nonword items no TMS responses were significantly slower than either TMS condition.

2.4 Discussion

Taken together the results indicate that the grammar classification task was not able to elicit a typicality effect, either measured by accuracy or response time, in either of the three conditions. However, downregulation of the right PAR did affect the response times to grammar classifications for both typical items and atypical items. This lends evidence to an account where text presented word level grammar judgements involve conceptual processing in the right PAR cortical region (Cappelletti *et al.*, 2010).

In the two-syllable lexical decision control task, it was possible to elicit the expected lexical effect for response time, where words had faster response times than nonwords, but not for accuracy. Within the word categories – words and nonwords – the no TMS condition was significantly slower than the left STG in words and significantly slower than both TMS downregulated cortical regions for nonwords. This indicated both cortical regions were involved in lexical decision processing to some degree. One possibility is this pattern lends evidence to the account where the left STG is involved in processing lexical information (Papagano et al., 2009) and that nonwords require both lexical information processing and conceptual processing (Cappelletti et al. 2010).

3 Experiment 2

Reading text involves the reconstruction of lexical stress from stored information in the mental lexicon (Aleman *et al.*, 2004). Making grammar classification judgements with text that either had typical or atypical stressed words did not elicit a typicality effect without TMS nor were responses affected by TMS pulses to the left STG or the right PAR. An alternative approach is to supply lexical stress information, as spoken items, and so that it is possible to strengthen the typicality effect (see Table 1 for summary).

[Please insert Table 1 about here]

Therefore Experiment 2 addressed the following research question: whether the left STG is sensitive to lexical stress information when this is provided, in a speeded grammar classification task. Alternatively, whether the finding in Experiment 1 was related to processes associated with lexical stress in text. The prediction is that there will be a typicality effect for the condition without TMS and the right PAR location. However, it is predicted that the left STG is involved in sensitivity to lexical stress. Therefore, the application of TMS to this region will attenuate the typicality effect between words with typical and atypical lexical stress patterns. As in Experiment 1, this will be as measured by accuracy and response times.

Results from the lexical decision control task found that accuracy – between words and nonwords – was similar across all conditions. However, response times were significantly faster for the left STG for words, compared with the no TMS condition, and significantly faster for both TMS conditions for non-words, compared to the no TMS condition. Although a comparison task, this extends what is known about the cortical regions that play a role in linguistic information (Coltheart et al., 1979). One approach to develop the findings further is to attempt to elicit a differentiation in lexical decision accuracy using word lists that require participants to draw on linguistic information in long term memory for both familiar (high frequency) and unfamiliar (low frequency) words. It is predicted that there will be a lexical decision frequency effect (i.e. more accurate responses and faster response times) in the condition without TMS and that there will be a similar pattern for both TMS locations.

3.1 Method

3.1.1 Participants

Twenty-one native English speakers took part in Experiment 2. Participants had a mean age of 25 years (*SD* = 4.26) and self-identified as right-handed (7 females and 14 males). No participants declared any form of reading difficulty, such as dyslexia, nor did they report English as a second language. One participant reported a childhood hearing impairment and was removed from the data analysis. All reported having normal or corrected-to-normal vision. As with Experiment 1, all participants were screened for exclusionary criteria in alignment with Rossi et al. (2009). A further five participants took part in piloting the speech materials.

3.1.2 Experimental Tasks

3.1.2.1 Grammar classification of lexically stressed items.

The task was presented through headphones, with the same word items as Experiment 1 (from Arciuli and Slowiaczek, 2007). The stimuli were recoded using a SL150 Microphone (EditorsKeys) by a native speaking British male. The audio was edited using Audacity (Team, 2012). The amplitude of the audio files was maximised by the software to be consistent across each item. Analysis of the audio files confirmed that strong syllables (*mean* = 141.92 Hz, *SD* = 15.62) had significantly higher pitch values than weak syllables (*mean* = 123.33 Hz, *SD* = 12.49), $t(38) = 4.66$, $p < .001$, $d = 1.32$. The duration of strong syllables (*mean* = 0.13 seconds, *SD* = 0.05) was also significantly longer than weak syllables (*mean* = 0.09 seconds, *SD* = 0.03), $t(38) = 4.83$, $p < .001$, $d = 1$. Moreover, the acoustic intensity of strong syllables (*mean* = 73.15 dB, *SD* = 4.28) was also significantly stronger than weak syllables (*mean* = 67.86 dB, *SD* = 6.12), $t(38) = 3.86$, $p < .001$, $d = 1.02$.

The experiment was conducted using OpenSesame (Mathôt *et al.,* 2012). Participants listened to the word and were asked to respond, as quickly as possible, as to whether the word was a noun or a verb. Six familiarisation trials were provided with accuracy and response time feedback, including feedback to respond faster than 2000ms, at the start of the experiment. Response times were recorded from the end of the audio file until the response made by the participant.

3.1.2.2 Lexical decision of high and low frequency words.

The lexical decision control task word list was modified so that it had a low frequency word list, high frequency word list, and nonwords (see Appendix B). These were selected from the English Lexicon Project database. Both sets of items had words that were six letters in length, with two syllables. They had a similar number of phonemes $t(37.75) = -1.61$, $p = .12$, $d = 0.51$ (high frequency phoneme *mean* = 5.30, *SD* = 0.47, low frequency phoneme *mean* = 5.55, *SD* = 0.51) but were significantly different in word frequency (HAL word frequency: high frequency *mean* = 12,792.25, *SD* = 6712.54, $n = 20$, low frequency *mean* = 1.75, *SD* = 1.37, $n = 20$, $t(38) = 8.52$, $p < .001$, $d' = 3.81$). Nonwords were also selected as filler items. A pilot study was conducted that confirmed participants were able to identify the words from non-words.

3.1.3 TMS Procedure

The procedure, counterbalancing, TMS pulse train, location, stimulation characteristics were the same as Experiment 1. Furthermore, it was decided to extend the interval between each condition. It was possible that there were carry over effects between one condition and the next where a 10-minute interval was used, as in Experiment 1, and this could attenuate the behavioural outcomes. In view of this, a 20-minute interval between each condition was used in Experiment 2.

3.2 Results

3.2.1 Grammar Classification.

A technical error with the audio file for the item “success” meant the responses to this item needed to be removed. Furthermore, an equipment failure resulted in the loss of data from one participant. This resulted in data from 19 participants being available for analysis. For accuracy and response time, linear mixed effects models with location and typicality as fixed effects and by-participants and by-items random intercepts were used. The analyses used the same functions and packages in R (R Team, 2015) as Experiment 1.

Accuracy was similar for typical and atypical items without TMS and at each location, $\beta = 0.83$, $SE = 0.32$, $p = 1$, left STG: $\beta = 0.94$, $SE = 0.36$, $p = 1$, right PAR $\beta = 0.73$, $SE = 0.28$, $p = 0.96$. Moreover, there were no significant interactions.

For response times, correct-only items that were also slower than 150ms were used and this resulted in the removal of 916 (21%) datapoints. Response times were similar in the condition without TMS, $\beta = 10.88$, $SE = 25.01$, $p = 1$, in the left STG, $\beta = 20.65$, $SE = 25.06$, $p = 0.96$, and the right PAR conditions, $\beta = 23.41$, $SE = 25$, $p = 0.94$. There were no significant interactions between location and typicality.

[Please insert Figure 6 about here]

[Please insert Figure 7 about here]

3.2.2 Lexical Decision.

For lexical decision, two linear mixed effects models were constructed, one for accuracy and another for response time. In both models, location and word frequency were added as fixed effect interactions. Participants and word items were added as random intercepts.

For accuracy, there were significant differences between high frequency and low frequency words for all three conditions: the condition without TMS, $\beta = 323.14$, $SE = 163.33$, $p < .001$, STG, $\beta = 338.08$, $SE = 177.3$, $p < .001$, and PAR, $\beta = 250.52$, $SE = 124.21$, $p < .001$.

There were also a number of significant interactions. These were between high frequency items of one condition and the low frequency items of another condition. The difference in accuracy between high frequency words in one condition and low frequency words in another condition was larger than the accuracy between TMS conditions within word frequency categories, high frequency no TMS > low frequency left STG: $\beta = 257.23$, $SE = 129.78$, $p < .001$, high frequency no TMS > low frequency right PAR: $\beta = 305.59$, $SE = 154.63$, $p < .001$, low frequency no TMS < high frequency left STG, $\beta = 0.002$, $SE = 0.001$, $p < .001$, low frequency no TMS < high frequency right PAR: $\beta = 0.004$, $SE = 0.001$, $p < .001$, low frequency left STG < high frequency right PAR: $\beta = 0.002$, $SE = 0.001$, $p < .001$, high frequency right PAR > low frequency left STG: $\beta = 210.88$, $SE = 104.5$, $p < .001$.

For response time analyses, items were included where they were correct and slower than 150ms, this resulted in the removal of 38 datapoints from the high frequency condition (1.76% high frequency) and 1421 datapoints from the low frequency condition (65.79% of low frequency datapoints). For all three location conditions, responses to high frequency words were significantly faster than for the low frequency words; no TMS, $\beta = -184.23$, $SE = 15.5$, $p < .001$, left STG, $\beta = -141.76$, $SE = 14.99$, $p < .001$, right PAR, $\beta = -170.86$, $SE = 15.32$, $p < .001$.

There were significant interactions where in each comparison the high frequency word response times were found to interact with low frequency response times of a different location condition. The difference was larger between high frequency words in one condition and low frequency words in another condition than between TMS conditions within word frequency categories, high frequency no TMS < low frequency left STG: $\beta = 154.01$, $SE = 15$, $p < .001$, high frequency no TMS < low frequency right PAR: $\beta = 166.37$, $SE = 15.39$, $p < .001$, high frequency left STG < low frequency no TMS: $\beta = 171.99$, $SE = 15.49$, $p < .001$, high frequency left STG < low frequency right PAR, $\beta = 154.12$, $SE = 15.38$, $p < .001$, high frequency right PAR < low frequency no TMS, $\beta = 188.72$, $SE = 15.55$, $p < .001$, high frequency right PAR < low frequency left STG, $\beta = 158.5$, $SE = 15.04$, $p < .001$.

[Please insert Figure 8 about here]

[Please insert Figure 9 about here]

3.2.3 Summary of findings from Experiment 2

In grammar classification, accuracy and response times were similar across all conditions. For lexical decision, accuracy was significantly higher and response times were significantly faster for high frequency words, compared with low frequency words, in all conditions. Where there were significant interactions, they were between responses to the high frequency words of one condition and responses to the low frequency words of another.

3.2.4 Discussion

Experiment 2 investigated whether the behavioural responses to word-level lexical stress sensitivity using speech presented items was affected by TMS pulses to the left STG or the right PAR. The typical and atypical lexical stress grammar classification task, designed with speech instead of text, was not able to elicit a typicality effect in the no TMS condition and the pattern of results was also found to be similar for the left STG and the, comparison, right PAR condition. One interpretation of the results is that both cortical regions, affected by TMS downregulation, were involved in speech modality lexical stress, since neither TMS condition showed a typicality effect. However, that the condition without TMS was also not able to elicit a typicality effect does not support this interpretation.

In the lexical decision control task, it was possible to elicit a word frequency effect, both for accuracy and response time. That this word frequency main effect was significant for all conditions, and that there were significant interactions between high frequency word conditions and low frequency word conditions, suggests that these two cortical regions are not related to processing lexical decision judgement within high and low frequency word conditions. This was in contrast to the findings in Experiment 1 that showed response time differences for the TMS conditions within the word and nonword conditions that were consistent with findings related to lexical information (Papagano et al., 2009) and object name processing (Cappelletti et al. 2010).

4 General Discussion

The aim of Experiments 1 and 2 were to investigate whether the left STG has a role in sensitivity to lexical stress. Previous neuroimaging studies have indicated that the left STG has a role in lexical stress sensitivity (Klein et al., 2011) and that areas of the right hemisphere were associated with sentence-level prosodic sensitivity (George *et al.*, 1996; Arciuli & Slowiaczek, 2007). However, there is still uncertainty about which cortical regions are involved in word-level lexical stress sensitivity. In addition to the left STG a control location, the right PAR, which is known to be involved in emotional processing but not specifically lexical stress processing (Hoekert et al., 2008; Cappelletti et al., 2010) and a condition with no TMS were also part of the design of the experiment. Two-syllable English words that had typical or atypical stress patterns for their grammar class were used as stimuli for the lexical stress task (Arciuli and Cuppels, 2004; Arciuli and Slowiaczek, 2007). A comparison task that involved lexical decisions to two syllable words was also used. In terms of cortical regions, lexical decisions have been found to be related to the left inferior frontal cortex (Edwards et al., 2005).

These two experiments contributed important knowledge to the field as they provided evidence of the circumstances where cortical regions are involved in sensitivity to word-level lexical stress and lexical decisions in English. The majority of words in the English language are multisyllabic, whereas the majority of studies in English focus on one-syllable words (Mousikou *et al.*, 2017), and these two experiments help contribute to the field's understanding of a wider range of words (Rastle & Coltheart, 2000, Perry et al., 2010).

The experiments found that although neither the text nor the speech presented items were able to elicit a typicality effect for word level lexical stress, response times for text presented judgements were affected by TMS pulses. For both typical items and atypical items, response times were faster in the right PAR condition than in the no TMS condition. Although left STG has been found to be involved in word processing (Klein et al., 2011), the parietal regions have been found to be involved in memory and motor response selection (Cappalletti et al., 2010). Therefore, one explanation is that this region activates during the response phase of the grammar classification task.

It was predicted that behavioural responses to the control task, the lexical decision task, would not be affected by TMS pulses applied to the left STG or the right PAR. This was the case for accuracy in Experiment 1. Although, response times to word items in Experiment 1 were significantly faster in the left STG condition, compared to the no TMS condition, and response times to nonwords were significantly faster for both the left STG and the right PAR. A similar pattern was not found for response times between high frequency and low frequency words in the lexical decision task of Experiment 2. This suggests that the left STG is involved in processing words whereas the processing of nonwords requires both regions. Although contrary to expectations, this is consistent with a view that the left STG is involved in some forms of word processing (Papagano et al., 2009) and that the right PAR is involved in response processing (Cappelletti et al. 2010). More generally, these findings could be interpreted to support the notion of the brain as, less modular, and more highly inter-connected (Andoh & Paus, 2011; Hilgetag, Theoret & Pascual-Leone, 2001; Klein et al., 2002).

The right PAR is also associated with attentional functions where top-down judgments are involved (Behrmann, Geng, & Shomstein, 2004; Howard et al., 2019), such as those that are likely to be made in either a lexical decision (Barca & Pezulo, 2012) or a grammar judgment. Both judgments require the activation of prior knowledge or rules and a defined response (Coltheart, Besner, Jonasson & Davelaar, 1979; Perry, Ziegler, & Zorzi, 2010; Rastle & Coltheart, 2000). This could result in lower accuracy and/or response times to stimuli. For most of the findings, the right PAR condition had a similar pattern to other conditions. However, it could explain the slower response times in the right PAR condition nonword judgments

(Experiment 1) as non-words require a different route to lexical decision judgments compared to words (Rastle & Coltheart, 2000).

4.1 Limitations and further considerations

It is possible that the findings arise because of cortical activation spreading. This is where TMS pulses to one location inhibit or disinhibit activity elsewhere in the brain and this has been documented by other researchers. Woźniak-Kwaśniewska *et al*. (2014) applied TMS to the dorsolateral prefrontal cortex and found, by measuring activation using electroencephalography, that pulses changed patterns of activity in contralateral locations. Although it is unlikely that the right STG has a substantial role in speech processing. For example, Shah-Basak et al. (2018) found that the right STG was involved in spatial judgments. In contrast, the left PAR has been found to play a role in some language functions, such as speech (Fridriksson et al., 2010) and writing production (Menon & Desmond, 2001).

A further methodological issue with TMS is that, since the effect is typically measured by behaviour it is not always clear whether the effect of TMS is consistent across the trials of the task (Hashemirad, Zoghi, Fitzgerald, & Jaberzadeh, 2017). Complementary to this is the possibility that the TMS conditions that did not result in attenuation of behavioural responses demonstrated this pattern because the TMS pulses had not induced neural changes. These limitations in TMS might have affected the results in this study.

It is also recognized that the sample size in these experiments might lead to analyses that are only able to detect moderate to large effects and therefore the findings should be interpreted with caution. However, the sample size ($N = 15$ in Experiment 1 and $N = 19$ in Experiment 2) is consistent with other TMS studies (for example, Hoekert, *et al*. (2008), $N = 14$; Papagno *et al*. (2009), $N = 12$; van Rijn *et al*. (2005), $N = 14$; and Woźniak-Kwaśniewska *et al*. (2014), $N = 20$).

A further, participant related, aspect of both experiments is the balance of males and females (69% female in Experiment 1, and 33% female in Experiment 2). It is possible that this could have affected the results. However, where researchers have studied sex differences in language processing with healthy adults, it is not typically the case that result patterns can be attributed to either group (e.g. Harrington & Farias, 2008).

Regarding the tasks themselves, it is possible that the differences in the pattern of results for both tasks is because of differences in their difficulty. Difficulty might have led to one task being more sensitive to TMS than the other. However, how task difficulty affects behavioral outcomes in TMS studies is still unclear. Beynel *et al*. (2019) found, in their individualized trial protocol, that it was the most difficult working memory trials that were most affected by TMS. However, in a dual task paradigm, Corp, Rogers, Youssef & Pearce (2016) were unable to invoke significantly different pattern of results in TMS applied to the motor cortex. Further research into the relationship between task difficulty and TMS is warranted and one possible account is that it is related to the operations involved in the task instead of difficulty itself (Walsh & Pascual-Leone, 2003).

A final task limitation is that the lexical stress task required participants to make grammar classification judgements instead of direct lexical stress assignment judgments. In effect, they were indirectly asked about the lexical stress of words. In some studies that have shown effects for lexical stress (e.g. Aleman et al., 2004; Kelly, 2004), participants are asked to identify the strong or weak syllable. However, it is likely that identifying nouns and verbs is a more natural language judgement compared with identifying specific syllables. Further studies could look to compare syllable identification with grammar classification.

4.2 Conclusion

The study here compared the target location, the left STG, with a control location in the right hemisphere (PAR), and a condition without TMS. In tasks that required participants to make judgement that involved text presented word-level lexical stress, inhibitory TMS to the right PAR affected response times for typical items and for atypical items. When items were presented as speech, no effect of TMS was observed. TMS pulses affected response times to word and nonword judgements for low frequency words. The findings are consistent with an account where the left STG is involved in some forms of word processing and the right PAR is involved in conceptual and object name processing in addition to processing the response itself.

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7 Declarations of Interest

Declarations of interest: none.

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Appendix A. Items for the lexical decision task in Experiment 1

Words	Nonwords
agents	aftery
artist	airmer
aspect	austif
camera	cament
campus	cargon
cities	carony
coffee	claced
column	crealy
combat	crunes
desert	decord
empire	easoer
folder	fidder
forest	forned
lyrics	lispel
packet	pables
parent	pamale
photos	photen
retail	rollet
sector	selped
sister	sladed

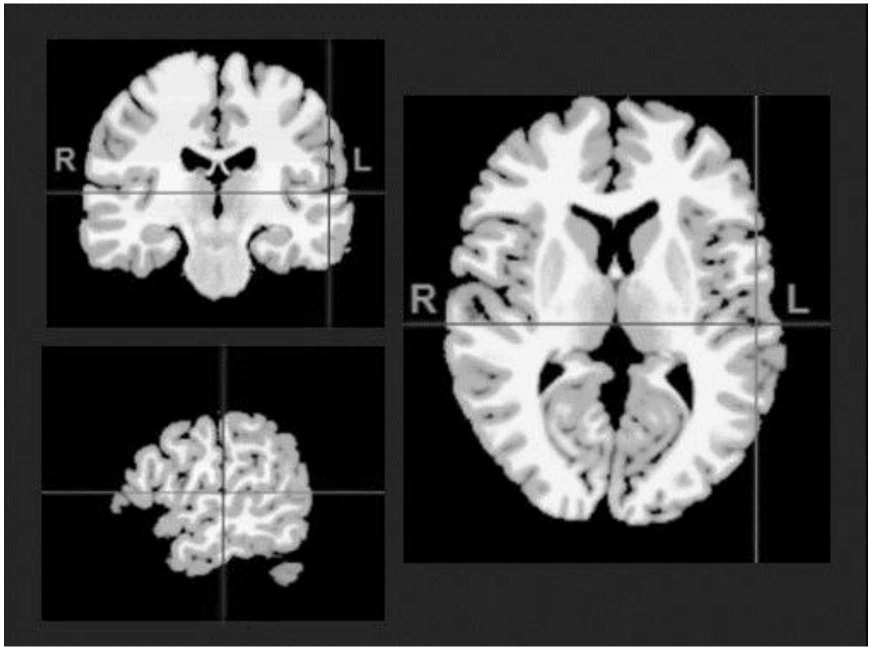
Appendix B. Items for the lexical decision task in Experiment 2

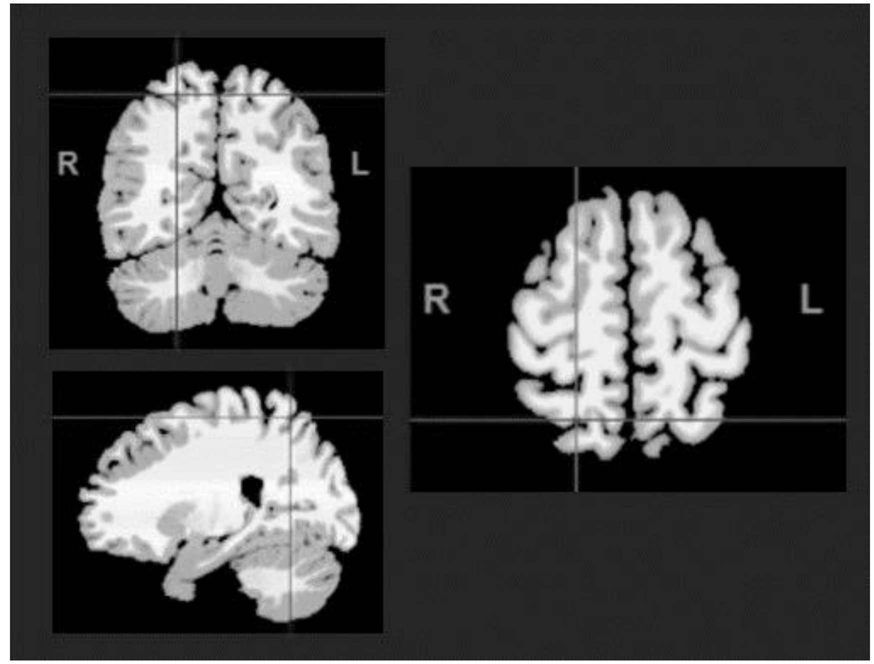
High Frequency	Low Frequency	Nonword
closer	bypath	glings
belief	cancan	atring
broken	corbel	clared
cancel	damson	dereve
cannon	elands	edated
demand	hatpin	erbing
dozens	immure	erders
escape	impend	fleric
finals	owlets	frings
frozen	palely	ganter
garden	pelmet	gercer
hungry	peruke	ifling
medium	poises	impere
mortal	punnet	linned
nearby	pupate	mantil
poorly	redact	nistil
rescue	runnel	pereal
spoken	tarsal	rorder
voices	upends	stimed
widely	viands	teroic

Table 1. Summary of the processing differences between the text and speech stimuli in Experiments 1 and 2

Experiment	Lexical Stress Sensitivity	Reconstructing lexical stress from text string	Reading	Forming response
Text stimuli	x	x	x	x
Speech stimuli	x			x

"x" indicates necessary processing for stimuli





Left STG location

Right PAR location (control)

Figure 1. The Talairach co-ordinates representing the left STG (x = -54, y = -21, z = 10) and right parietal location (x = 24, y = -56, z = 54).

The co-ordinates are mapped onto a standard brain image using the MNI2TAL app on BioImage Suite (NIH Brain Initiative).

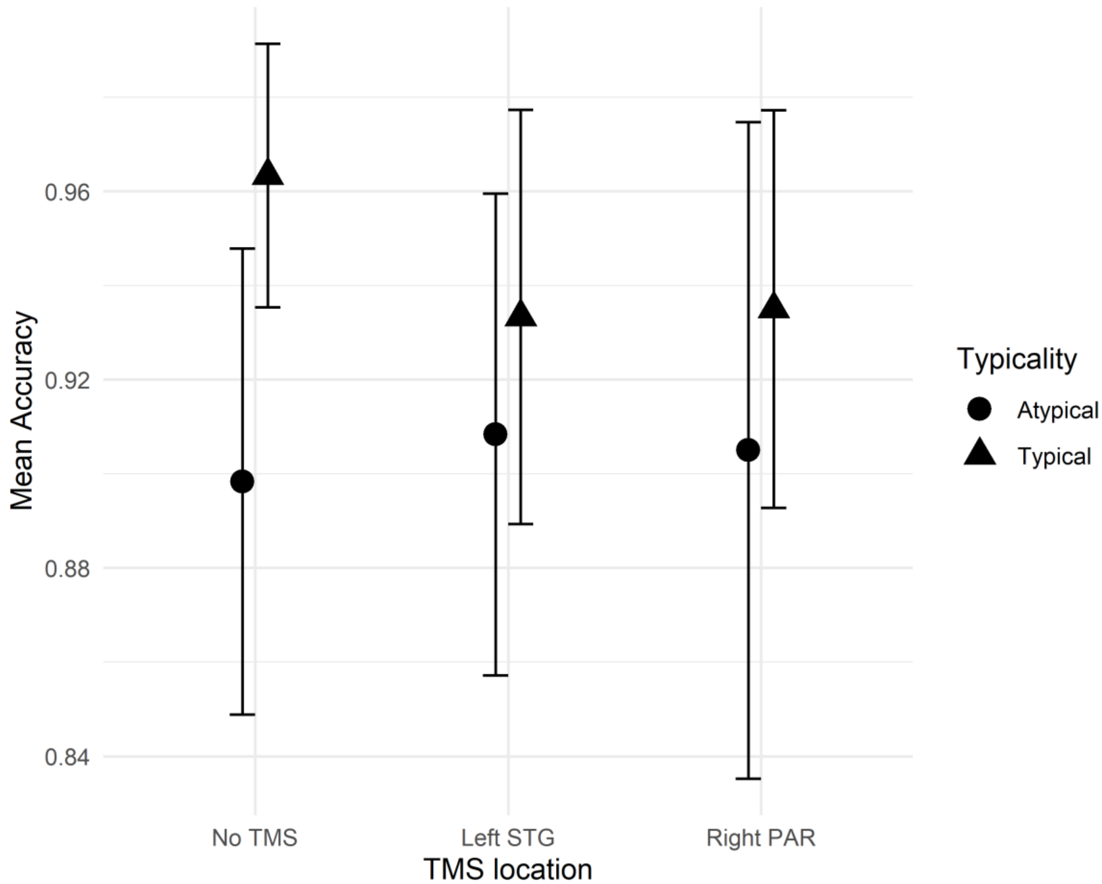


Figure 2. Mean accuracy of grammar classification judgements to text for location and typicality, error bars are 99% confidence intervals.

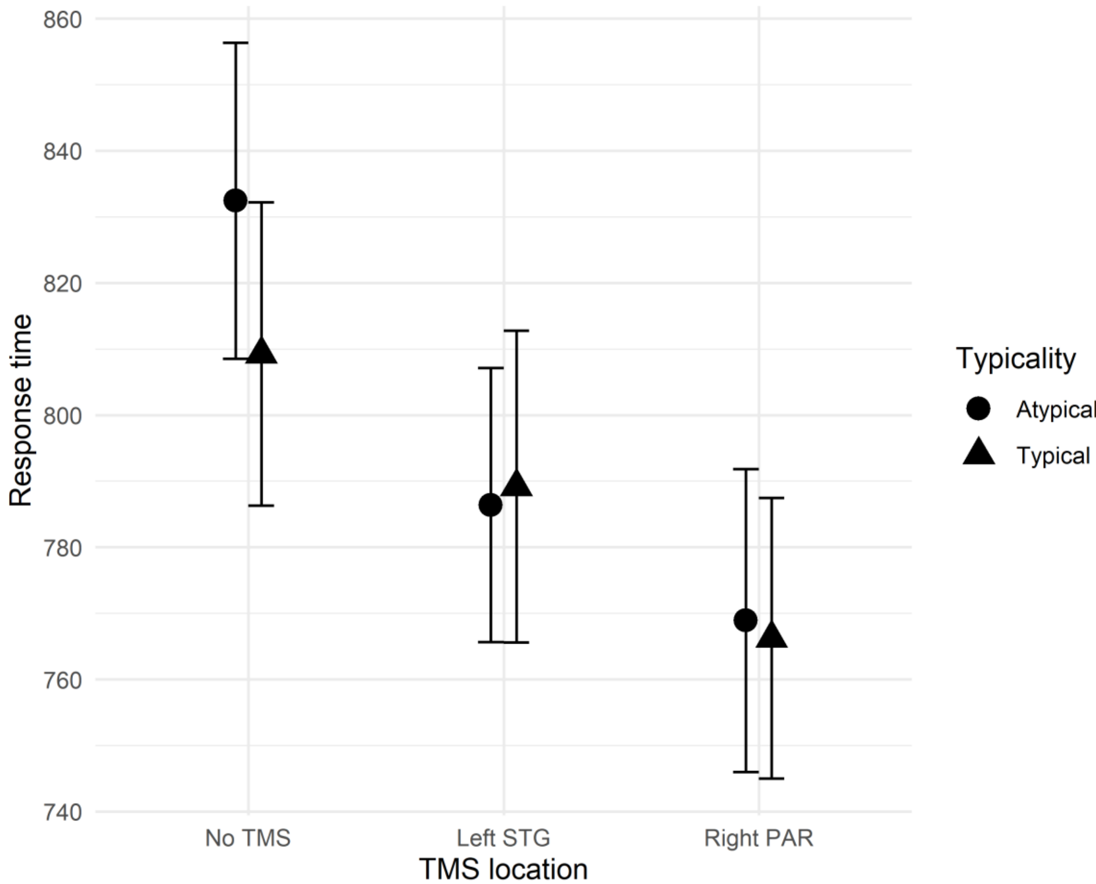


Figure 3. Mean response times of grammar classification judgements to text for location and typicality, error bars are 95% confidence intervals.

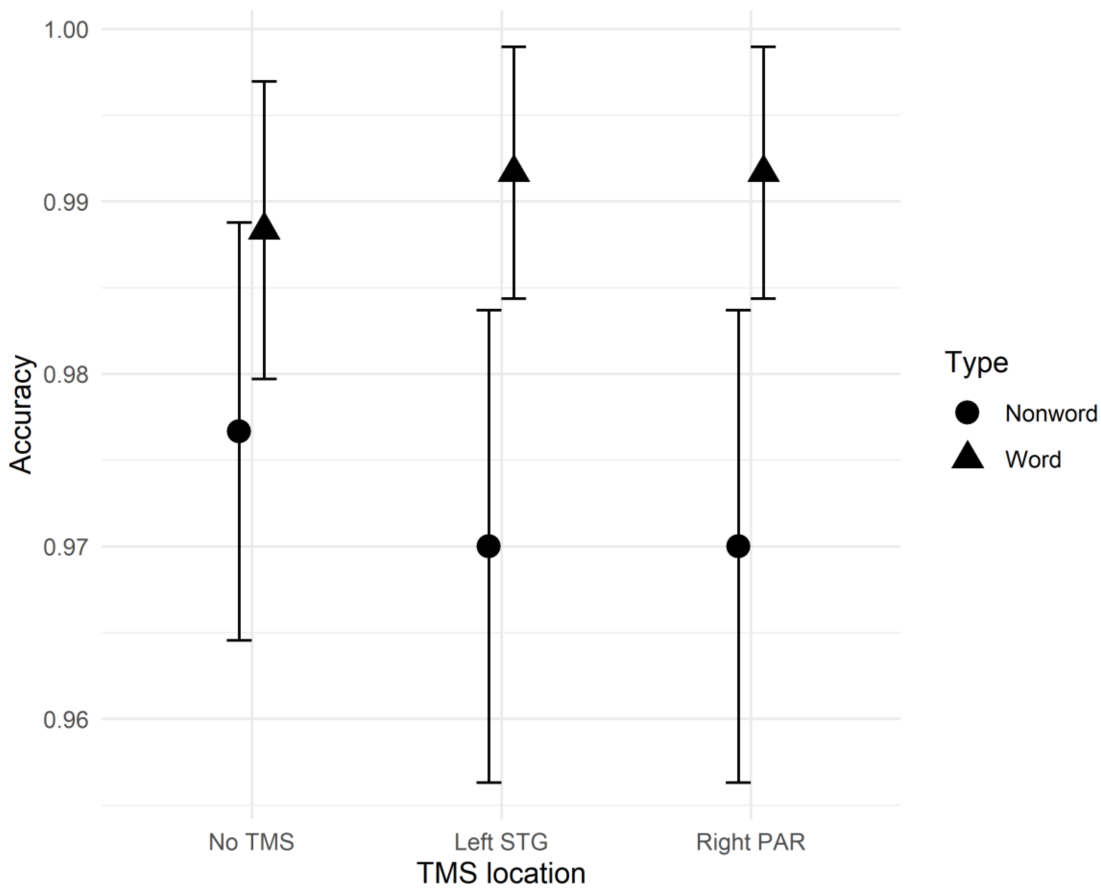


Figure 4. Mean accuracy of lexical decisions for location and word type, error bars are 95% confidence intervals.

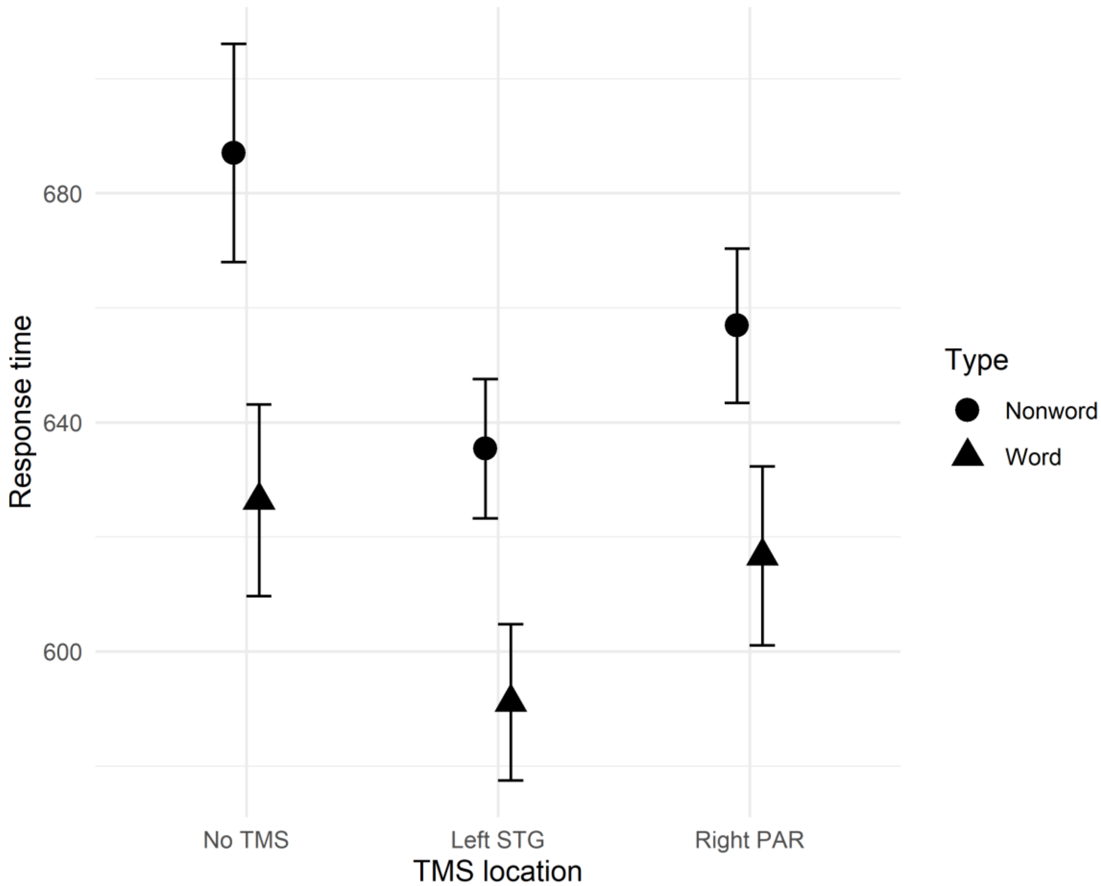


Figure 5. Mean response times of lexical decisions for location and word type, error bars are 95% confidence intervals.

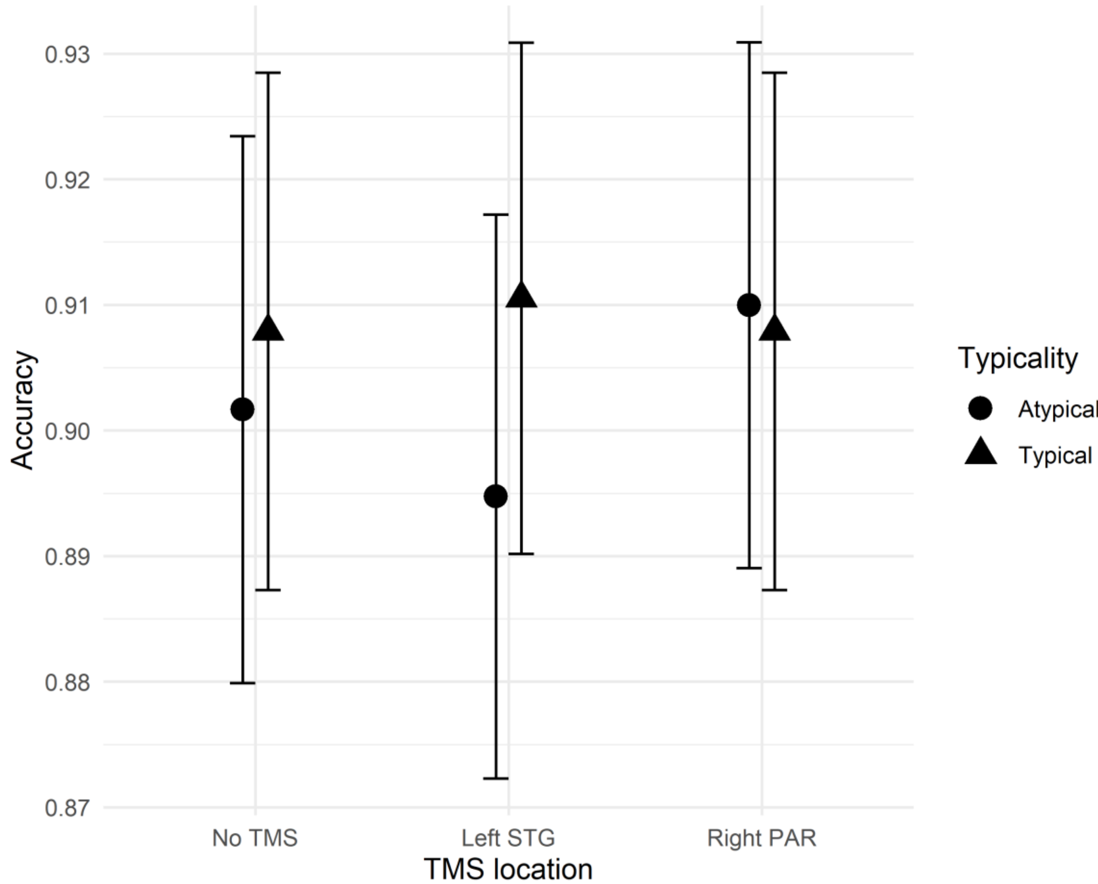


Figure 6. Mean accuracy of grammar classification judgements to spoken words for location and typicality, errors bars are the 95% confidence intervals.

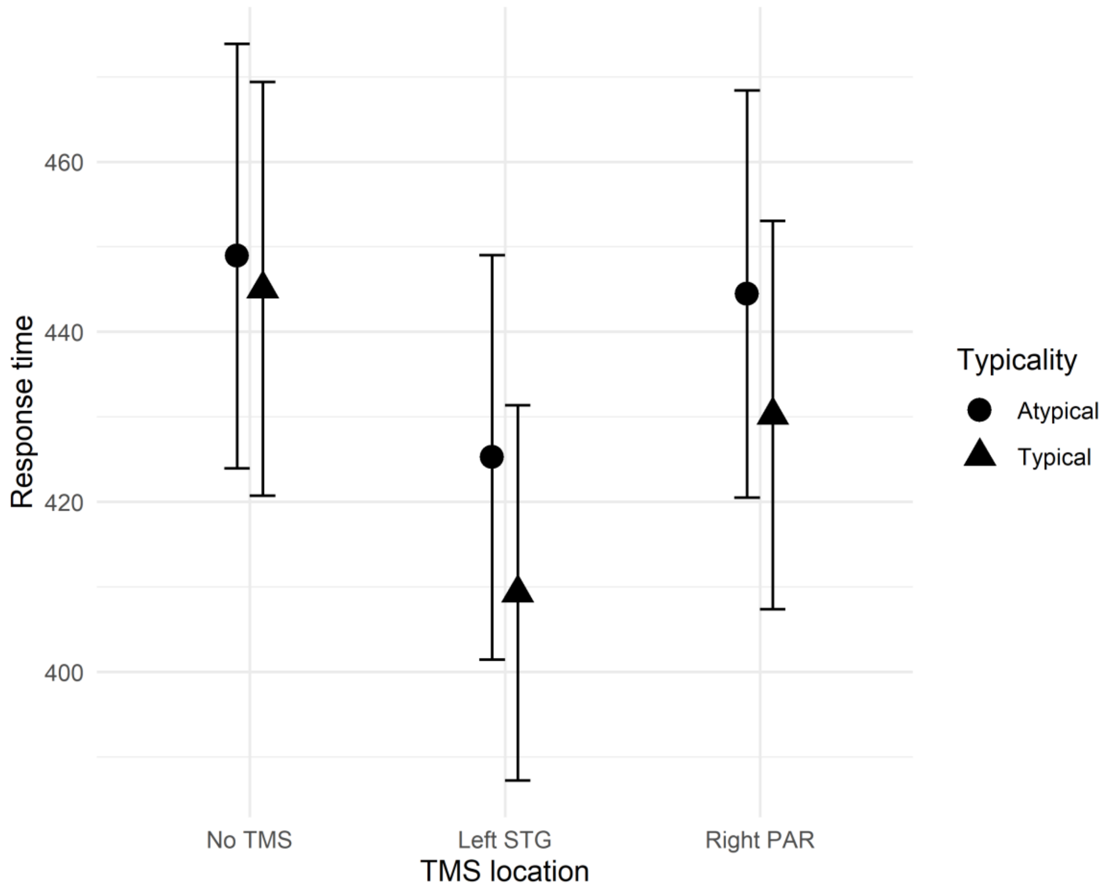


Figure 7. Mean grammar classification response times to spoken words for location and typicality, errors bars are the 95% confidence intervals.

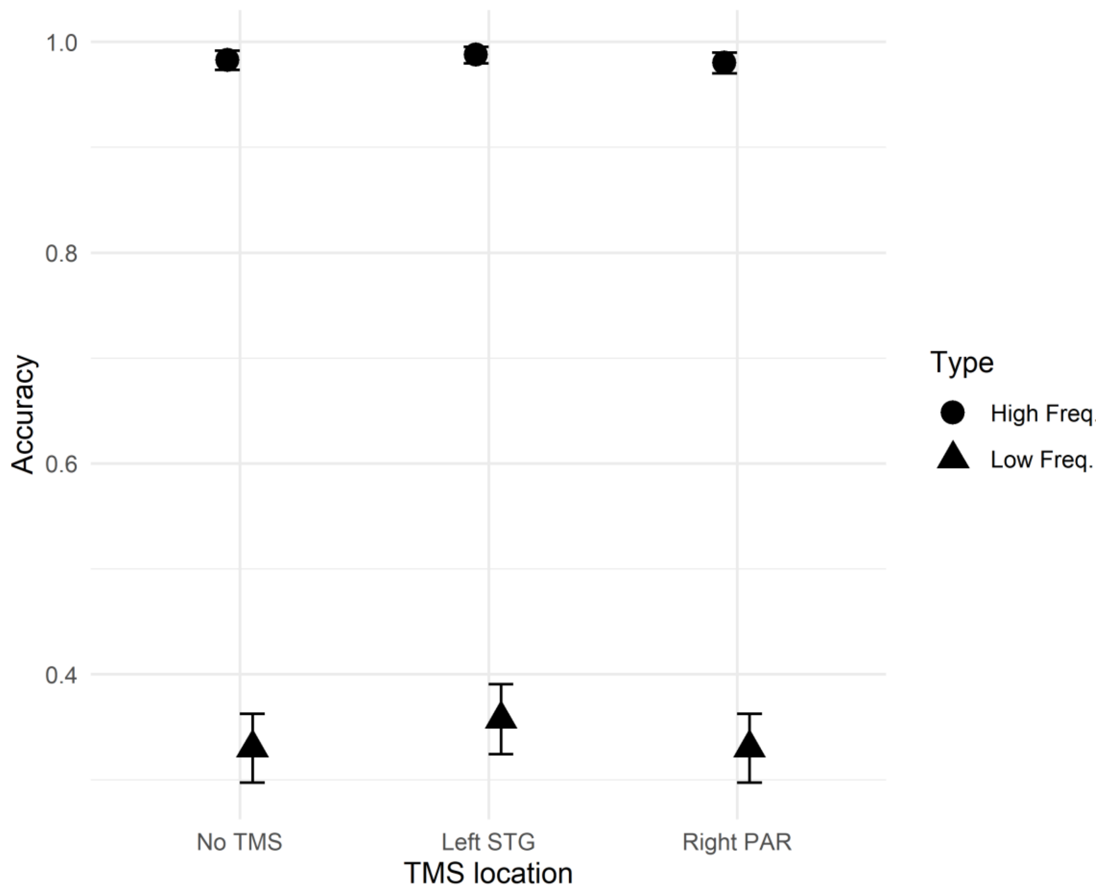


Figure 8. Mean accuracy of lexical decisions for location and word frequency. Error bars are the 95% confidence intervals.

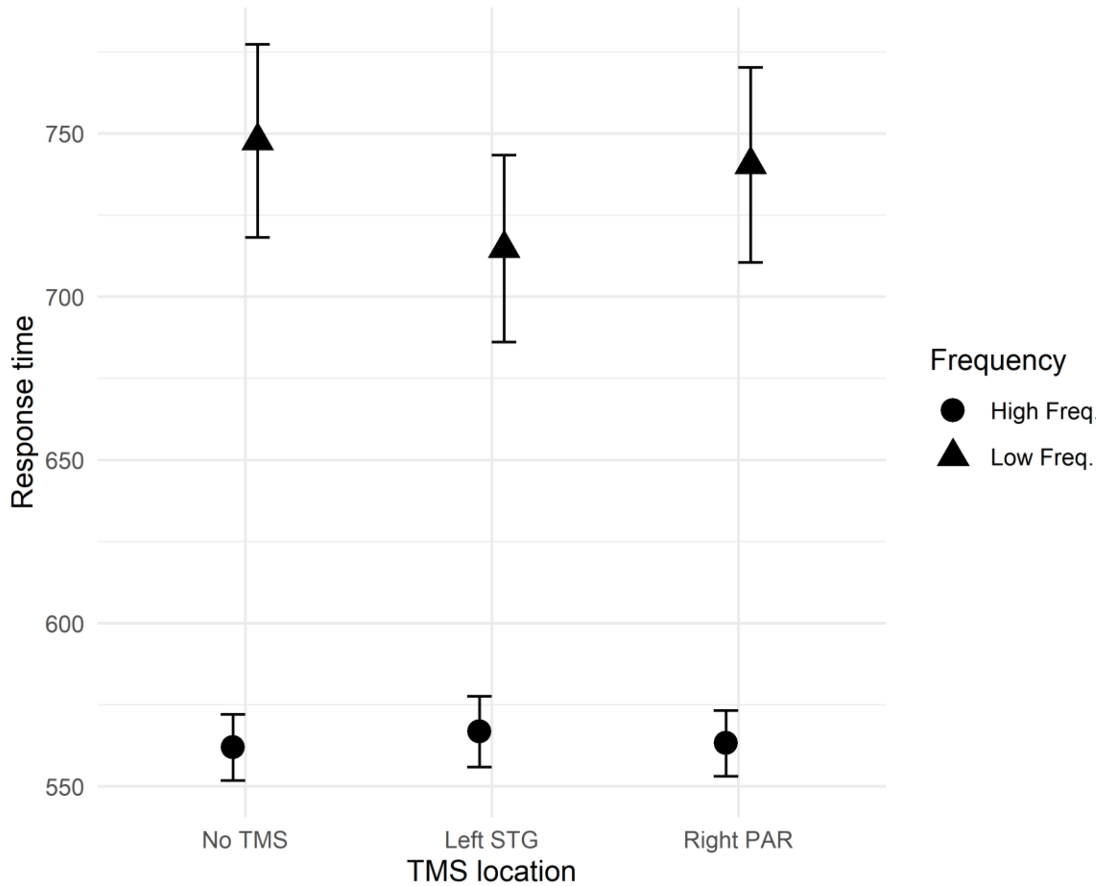


Figure 9. Mean response times of lexical decisions for location and word frequency. Error bars are the 95% confidence intervals.